Public Safety and Emergency Preparedness Canada
Critical Infrastructure Protection and Emergency Preparedness

Sécurité publique et Protection civile Canada
Protection des infrastructures essentielles et Protection civile

Catastrophic Landslides and Related Processes in the Southeastern Cordillera:

ANALYSIS OF IMPACT ON LIFELINES AND COMMUNITIES

104-06746/

Acknowledgements

This publication has been prepared for:

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This material is based upon work supported by the Division of Research and Development (DRD) in the Office of Critical Infrastructure Protection and Emergency Preparedness (OCIPEP), under Contract Reference No. 2001D002. OCIPEP is now a part of Public Safety and Emergency Preparedness Canada (PSEPC). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of Public Safety and Emergency Preparedness Canada.

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Catalogue No.: PS48-2/2004E-PDF
ISBN: 0-662-36221-7

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Executive Summary

Landslides are a major natural hazard in Canada since they impact on communities, lifelines and both regional and national economies. Landslides have caused over 600 deaths across Canada since the middle of the 19th century. In addition, communities have been damaged, lines of communication have been severed, and the resource base has been significantly impacted. Recent studies of the geographic distribution of the impact of landslides in Canada has indicated that the Canadian Cordillera, comprising about one-fifth of Canada's land mass, is the region most prone to damaging landslides.

The southeastern Cordillera (roughly defined by the Trans-Canada Highway to the north, the Foothills to the east and the Okanagan Valley to the west) has been the site of a number of catastrophic landslides including the 1903 Frank Slide, Canada's worst landslide disaster. The region is crossed by national strategic transportation corridors, has important natural resources, and has extensive areas of designated natural heritage. The record of damaging landslide events in historical time has been compiled from existing case history documents, archival information, and information supplied by transportation companies and government agencies. The record has been assembled in a relational database.

Major damaging landslide types have been identified as follows; rock avalanches, rockfalls, rainfall-triggered debris flows and debris avalanches, landslides in built slopes, and landslides in slopes consisting of glaciolacustrine deposits. Deforming rock slopes, however, constitute a hazard that is difficult to assess. At one strategic site digital elevation models have been useful in characterizing surface changes.

A regional definition of landslide risk has been attempted for the southeastern Cordillera and the role of such factors as human activity and climate in determining landslide frequency has been analysed. The study provides a framework for a regional hazard assessment and for evaluating mitigation measures, emergency preparedness and landslide disaster response strategies for the region.

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1.0 Introduction

1.1 Background

Landslides are a major natural hazard in Canada since they impact on communities, lifelines, and regional and national economies (Evans, 2001). Landslides have caused over 600 deaths across Canada since the middle of the 19th century (Evans, 1997, 2001). In addition, communities have been damaged, lines of communication have been severed, and the resource base has been significantly impacted.

Recent studies of the geographic distribution of the impact of landslides in Canada (Evans, 2001) has indicated that the Canadian Cordillera, comprising about one-fifth of Canada's land mass, is the region most prone to damaging landslides. Extensive work has been undertaken on landslides in the southwestern Cordillera as reviewed by Evans and Savigny (1994). In this study we focus on landslides in the southeastern Cordillera.

The southeastern Cordillera is roughly defined by the Trans-Canada Highway to the north, the Foothills to the east and the Okanagan Valley to the west, and includes southeast British Columbia and parts of southwest Alberta. The region is crossed by national strategic transportation corridors, has important natural resources, and has extensive areas of designated natural heritage.

Lifelines and communities in the southeastern Cordillera are vulnerable to catastrophic landslides. In addition to experiencing Canada's largest landslide disaster, the 1903 Frank Slide in which approximately 70 people died, lifeline infrastructure has recently been subjected to damaging landslides. The occurrence of a rainfall-triggered debris avalanche at Passmore, in the Slocan Valley of southeastern British Columbia, in April 2000 has pointed to the hazard posed by such processes and has illustrated the impact that they have on the lifeline infrastructure of the southern Cordillera. The Passmore slide severed power lines and telephone cables leaving more than 4,000 area residents without power and telephone service. The slide also blocked British Columbia Highway 6 for several days disrupting transportation in the region.

Other recent landslides have impacted on lifelines in the region (e.g., the 1999 Banff debris flow (Couture and Evans, 2000a) cutting buried fiber optic cables, disrupting transportation and in some cases resulting in costly derailments (Evans, 1999). In addition, recent landslides have also impacted on communities (e.g., the 1999 Swansea Point debris flow).

The lifeline infrastructure of the southeastern Cordillera is vital to both regional and national economies. For example, transportation links through the area are vital conduits for key Canadian exports such as wheat, coal, and potash. Communities in the region are growing. The area has a growing population, a flourishing tourist industry, and important primary resource industries.

1.2 Objectives

The objectives of the present work are as follows:

1. To assemble a detailed database of historical damaging landslides in the study areas. The database will be in Microsoft® Access and maps will be in digital form.

2. To develop an analysis and hazard assessment of a selection of representative historical event case histories, including rock avalanches, rockfalls, debris flow, landslides in built slopes, and landslides in glaciolacustrine materials.

3. Examine the implications of temporal aspects of the event record for Emergency Preparedness, including the frequency of occurrence of slide types, typical triggers, and possible change of frequency in time.

4. To develop a first approximation to a regional landslide risk model.

2.0 Regional Characteristics

Geomorphology and geology – The southeastern part of the Cordillera is formed of several and distinct mountain ranges separated by deep valleys in a north-south orientation. Numerous elongated lakes as well as two important rivers – the Columbia and Kootenay rivers – are fed by vast quantities of fresh water released from winter snow-pack through tumbling creeks.

Two of the five geomorphologic belts forming the Canadian Cordillera make up the region: the Foreland and Omineca belts (Gabrielse et al., 1991; Figure 2-1). The Foreland Belt forms the eastern mountain ranges and foothills of the Canadian Cordillera, in southeastern British Columbia and southwestern British Columbia. Its eastern boundary is marked by the eastern limit of deformed strata of the Foothills. Its western boundary coincides with the Rocky Mountain trench. In the Foreland Belt, rock formations contain mainly sedimentary rocks from Precambrian to Early Tertiary ages, including crystalline basement gneiss and carbonate-clastic rocks. The belt contains a minimum thickness of about 15 km of Precambrian, Palaeozoic, Mesozoic, and early Tertiary sedimentary rocks in a series of stacked thrust sheets.

The Omineca Belt is located between the Foreland and the Intermontane belts. The Omineca Belt comprises a series of northwesterly-aligned structural elements and includes the high and rugged Purcell, Selkirk, Columbia, Monashee, and Cariboo mountain ranges. It is dominated by abundant metamorphic rocks with lesser amounts of granitic rock. The metamorphic rocks are complexly folded and faulted, and represent the exposed roots of a mountain chain that formed between 180 and 60 million years ago.

Mineral resources and energy – The southeastern part of British Columbia is also recognized for its main deposits of precious metals, such as gold, silver, and platinum-group elements (Dawson et al. 1991). In the studied area, petroleum resources are mainly confined to the Foreland Belt. Also, vast resources of bituminous and sub-bituminous coal and lignite occur in the Foreland Belt and are mined in gigantic open pits.

Population and settlement – The study area covers 88,732 km^2. The population is approximately 475,220 indicating a population density of 5.4 persons/km^2. The economic importance of the Beaver River Valley has long been recognized. The route was first discovered and utilized by the Canadian Pacific Railway (CPR) in the late 19th century. The Trans-Canada Highway was constructed along the corridor in the early 1960s and a second CPR line was completed in the late 1980s.

Over 1.5 million vehicles pass through the Roger's Pass every year. During the summer months, about 6000 vehicles per day travel through the segment (personal communication, Glacier National Park). In addition, about 40 trains per day travel on the CP Rail mainline for a total of over 14,000 trains per year (personal communication, CPR).

Figure 2-1 Geologic belts and main mountain ranges in the southeastern Cordillera (after Gabrielse et al., 1991).

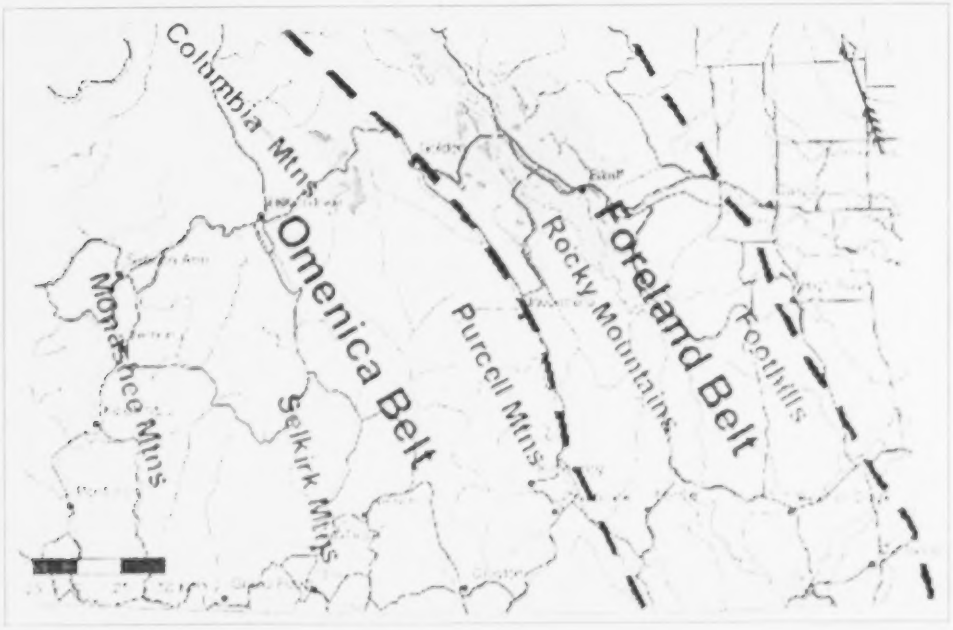
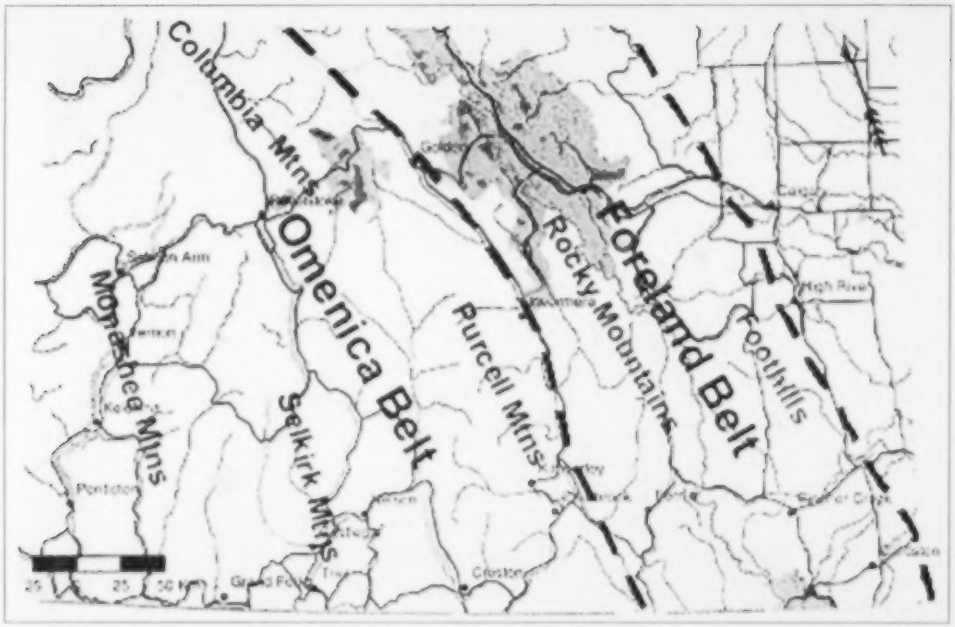


Figure 2-1 Geologic belts and main mountain ranges in the southeastern Cordillera (after Gabrielse et al., 1991).



3.0 Damaging Landslide Types and Related Processes

A number of damaging landslide types and related processes are active in the southeastern part of the Cordillera. They include the following:

1. *Rock avalanches* involve the initial failure and subsequent disintegration of a large rock mass on a mountain slope and the rapid downslope movement of this debris into a valley. The term was first used by Geological Survey of Canada geologists to describe the 1903 Frank Slide, in the Rocky Mountain Foothills of Alberta (McConnell and Brock, 1904). Rock avalanches are typically greater than 1 M m^3 in volume and can be very mobile i.e., debris may travel long distances (up to 10 km in some Cordilleran cases) from their source. Rock avalanches are the fastest type of landslide and may reach very high speeds. Fore example, according to eye witnesses the 1903 Frank rock avalanche had a duration of about 100 seconds in its travel over 3.12 km, indicating an average velocity of 31.2 m/s (112 km/h). Rock avalanches are very destructive when they impact on human activity, as exemplified by the Frank Slide which struck the outskirts of the town of Frank, Alberta killing approximately 70 people. A large number of prehistoric rock avalanche deposits exist in the southeast Cordillera, especially in the Rocky Mountains (e.g., the Kananaskis Lake rock avalanche). The largest prehistoric rock avalanche known in the region is the Valley of the Rocks deposit (est. vol. 1B m^3) in the Rocky Mountains of southeastern British Columbia (Evans, 2001). Another huge deposit is that of a pre-historic rock avalanche at Three Valley Gap. It originated from the eastern slopes of Mount Griffin, filled the valley and formed Three Valley Lake, a landslide-dammed lake.

2. *Rapid Rockslides* are transitional to rock avalanches. They occur when a rock mass slides on a detachment surface, such as a bedding plane or fault surface, and the debris only partially leaves the source area. Most of the debris is deposited only a limited distance downslope. *Slow rockslides* are transitional to mountain slope deformation, and are limited in displacement but show well-defined lateral shear surfaces and a recognizable headscarp (Mt. Mackenzie).

3. *Mountain slope deformation* is a problematic process related to slow sliding, and consists of slow, deep-seated movement of a large rock mass that commonly exhibits loosening and fracturing in the sub-surface, and signs of disturbance on the slope surface. The process is termed "sagging" and may represent an early phase in the development of deep-seated landsliding in mountainous terrain. This type of slope movement may involve movement along discrete shear surfaces and/or deep-seated mass creep. It is manifested in topographic features such as cracks, fissures, trenches, antislope scarps[1] at mid or upper slope locations, and, in some cases, slope bulging at lower slope locations. These linear geomorphic features are termed "sackungen," after the German word for sagging. The features generally occur without well-defined headscarps, lateral scarps, or lateral shear zones, suggesting that slope movement is occurring without the formation of well-defined shear surfaces (unlike rockslides). Sackungen are widespread throughout the southeastern Cordillera, especially in the metamorphic rocks of the Columbia Mountains.

[1] An antislope scarp is a bedrock scarp that faces uphill and is formed by differential rock slope deformation.

4. *Rockfall* involves a much smaller rock mass than rock avalanches or rapid rockslides. In a rockfall, the rock mass disintegrates into numerous blocks that fall, bounce, and roll on steep slopes after detachment from a rock slope. Rockfalls are typically less than 50,000 m^3 but may attain high velocities in the range 35–40 m/s (126–144 km/h). Rockfalls are a constant problem along transportation routes through southeastern Cordillera and have also impacted on buildings located below bedrock slopes (e.g, 1983 Sunnybrae rockfall). Exposure to rockfall hazard along transportation routes has been reduced by rock slope stabilization, rockslope protection, and the installation of rockfall warning fences. In other cases rockfall hazard has been reduced by the excavation of ditches or the erection of cable net fences across a slope both of which are designed to catch rolling or bouncing boulders before they reach buildings further downslope.

5. *Debris flows* are a common rainfall triggered landslide (e.g., Evans and Lister, 1984). They are frequently generated by the channelisation of an initial debris avalanche triggered in the steep upper slopes of a watershed (e.g., the 1997 Hummingbird Creek debris flow). In other cases, streambed material may be mobilized when stream discharge exceeds a critical threshold such as during a severe rainstorm or as a result of a sudden draining of an ice-dammed or moraine-dammed lake (e.g., Mt. Macoun; Evans, 1987; Clague and Evans, 1994). They may also be triggered by the impact loading of stream bed materials by rockfalls or falls of glacier ice (e.g., Mount Stephen debris flows).

6. *Debris avalanches* are common in forested steeplands. Landslide volumes generally range from 20,000 to 60,000 m^3. Debris avalanche paths may exceed 500 m in length but involve only a very thin veneer (less than 2 m) of surficial materials. Based on eyewitness accounts, the velocity of debris avalanches commonly exceeds 10 m/s (36 km/h). An analysis of the 1990 Belgo Creek debris avalanche (estimated volume 23,000 m^3) by Hungr (1997a) indicated local velocities as high as 20 m/s (72 km/h). The behaviour and occurrence of debris avalanches is in contrast to channelised debris flows which generally recur in a channel course and the velocity of which rarely exceeds 7–8 m/s (25–28 km/h).

7. *Landslides in glaciolacustrine silt I* – slow slides and rapid flows are also the characteristic style of landslides in the glaciolacustrine sediments deposited in glacial lakes that existed in most valleys in the southeastern Cordillera during the Pleistocene. Glaciolacustrine sequences are characterized by interbedded silt and low-strength clay sediments. In addition, these sediments are commonly inter-layered with occasional sand partings in which excess pore pressures may develop. Sensitive materials have sometimes been encountered in glaciolacustrine sequences. Failure geometries range from simple rotational slides to compound movements in which the sliding surface consists of multiple planar elements determined by the attitude of such features as fissures, laminations, and bedding. Many urban centres in the region are built on glaciolacustrine sediments and landslides in these materials have impacted on sites along river banks and lakeshores. In the Okanagan valley numerous slope stability problems have been encountered along the shores of Okanagan Lake (e.g., Evans, 1982).

8. *Landslides in glaciolacustrine silt II* – Siltfalls involve falls of dessicated or cemented glaciolacustrine deposits that form high bluffs. They commonly originate in thin slab-like

slides which involve failure through the base of the slab. They may also result from toppling. Siltfalls originate from bluffs developed in Pleistocene glaciolacustrine silt in the semi-arid areas of southeastern British Columbia (Evans, 1982). Blocks involved in the siltfall disintegrate upon hitting the debris slope and may flow in a manner similar to a granular avalanche (Hungr et al., 2001). As the Summerland earthfalls of 1970 and 1992 illustrate (see case history in Section 5.4) such a process can be highly destructive. Siltfalls occur very rapidly and without warning.

9. *Subsurface erosion and collapse: the phenomenon of piping* – Special geotechnical problems are encountered in glaciolacustrine silt deposits in the semi-arid valleys of the south-central and south-eastern Cordillera notably in the South Thompson, southern Okanagan, and Upper Columbia valleys. The silts are thought to have been deposited rapidly in ice-marginal glacial lakes during Late Pleistocene deglaciation (Fulton, 1975; Nasmith, 1972; Haughton, 1978). Piping (subsurface erosion), ground collapse (the sudden decrease in volume of the material due to wetting), and ground caving (the failure of a tunnel or pipe roof) has resulted in the widespread occurrence of sinkholes, depressions, and related geomorphic features (Miller and Nyland, 1981; Haughton, 1978).

10. *Landslides in built slopes* – significant landslides can result from the failure of man-made road and rail embankments, excavated rock slopes, and mine waste dumps. These types of landslides have been termed *geotechnical failures*. Although they are not natural landslide events *sensu stricto* they do involve re-worked natural materials and are frequently caused by extreme hydrometeorological conditions (e.g. heavy rainfall, rapid melting of snowpack) or earthquake shaking. Some of the largest landslides in Canada in recent years have occurred on the slopes of gigantic waste dumps at open pit coal mines in the Rocky Mountains of southeastern British Columbia where ten mines currently generate 200–250 M m^3 of rock waste per year. The waste is disposed in huge dumps constructed by end-tipping from dump trucks. Over 50 high-velocity long-runout flowslides resulting from failures of these dumps have been documented since 1972; at least nine flowslides involving volumes in excess of 1 M m^3 occurred in the period 1971 to 1993 culminating in the gigantic 8 M m^3 1993 failure of Fording Coal's South Spoil in the Fording Valley. Peak velocities of this type of flowslide may reach 40 m/s (144 km/h). Failure in the dumps is closely monitored and prediction of complete slope failure is possible based on deformation-time plots. Coal mine waste dump failures have claimed nine lives in southeastern British Columbia in the period from 1968 to 1996. Rapid landslides also occur in road and railway embankments, often with disastrous results (e.g., Evans, 1999). Failure may take place within the embankment fill itself, or involve a basal failure in the embankment foundations.

11. *Secondary Effects of Landslides I: Landslide-generated waves* – Where rapid landslides enter rivers, lakes, or artificial reservoirs they may generate destructive water waves, also known as landslide tsunamis (e.g. the 1903 Arrow Lakes rockfall and wave). They may also occur when a subaqueous landslide occurs in a lake or reservoir.

12. *Secondary Effects of Landslides II: Landslide dams* – Landslide dams form where landslide debris blocks natural drainage. The formation of landslide dams cause damage upstream due to back-flooding, and downstream due to an outburst flood which may develop as a result of a sudden dam break.

13. *Glacier-related hazards* – This group of hazards is related to glacier behaviour (advance or retreat) and the instability of the glacier during retreat. Glacier hazards include glacier avalanching, glacier outburst floods (jokulhlaup) either from lakes ponded by a glacier dam or from pockets of water within or on the surface of the ice, and outbursts from the failure of moraine-dammed lakes. These hazards are prevalent in the southeast Cordillera where debris flows generated by glacier outburst floods have been particularly problematical (e.g., Cathedral Mountain).

14. *Snow avalanches* are only mentioned to complete the range of slope-related hazards encountered in the southeastern Cordillera. Heavy losses were experienced in the early development of the region, particularly with respect to railway and mining activity (Stethem and Schaerer, 1979, 1980, Schaerer, 1987; Jamieson, 2001). Between 1885 and 1962, 200 people died in snow avalanches on the railway in Glacier National Park alone. The construction of the Trans-Canada Highway through Rogers Pass necessitated the development of one of the most advanced programs of snow avalanche prediction, control, and protection in the world (Schleiss, 1990). With the increase in heli-skiing and other types of back-country skiing, a rising number of fatal recreational accidents have occurred in the region due to snow avalanches (Jamieson and Geldsetzer, 1996). During Winter 2001–2002, seven of the 11 persons killed in snow avalanches in the Canadian Cordillera lost their lives in southeastern British Columbia (Canadian Avalanche Centre, 2002).

4.0 Damaging Landslide Database

A total of 58 landslides are listed and described in a Microsoft® Access 2000 database. These events are mostly historical; going back to the late 19th century, but some are quite recent.

Figure 4-1 shows the study area with the locations of the landslides. For comparison purposes, large settlements were also included on the map, as well as provincial and federal parks (green area), contour intervals (green lines), and major roads (black lines) and rivers (blue lines). This map does not reflect the numbers of landslides reported since some of these have more or less the same coordinates and are represented by the same star. Basic information on these 58 slides is presented in Table 1.

Table 1 Damaging Landslide Summary Table

Name of Landslide	Location Name	Date of Occurrence	Latitude (deg.-min.-sec.)	Longitude (deg.-min.-sec.)	Primary Landslide Type	Near Community (y/n)	Presence of Infrastructure (y/n)	Type of Human Activity in Area
Sheep Creek	Rossland	1897-04-20	49-01-37.2	117-49-44.3	Debris flow	n	y	Railway construction
Sandon-Kaslo area	Kaslo-Sandon	11/03/1900			Rock slide	y	n	Mining
Rambler McGuigan basin, near Kaslo	Kaslo	08/05/1902			Unknown	n	n	
Upper Arrow Lake	Arrowhead Provincial Forest	28/02/1903	50-41-51.1	117-52-30.5	Rock fall	y	y	
Rossland	Rossland	01/04/1903	49-xx-xx	117-xx-xx	Unknown	y	y	
Frank	Frank	29/04/1903	49-33-25.9	114-24-21.1	Rock avalanche	y	y	Mining
Shelter Bay, Upper Arrow Lake	Arrowhead Provincial Forest	11/03/1908	50-xx-xx	117-xx-xx	Subaqueous landslide	n	n	Logging
Okanagan Lake, near Penticton	Penticton	20/07/1951	49-xx-xx	119-xx-xx	Silt fall	y	y	
Wynndel, near Creston	Creston	02/04/1956	49-xx-xx	116-xx-xx	Debris flow	y	y	
(near) Nelson	Nelson	07/04/1957	49-xx-xx	116-xx-xx	Debris flow	n	n	
Revelstoke	Revelstoke	12/12/1959			Debris slide	n	n	
Bastion Mountain	Shuswap Highland Provincial Forest	22/12/1959	50-46-xx	119-15-xx	Rock fall	y	y	
Twin Butte	Arrowhead Provincial Forest	11/05/1961	51-00-29.1	118-00-11.5	Debris slide	n	y	
Camp Creek	Eagle Provincial Forest	05/06/1968	50-59-27.6	118-28-39.7	Debris slide	n	y	
Victor Lake, east of Revelstoke	Revelstoke	26/08/1968			Rock fall	n	n	
WB, Balmer Pit, no. 2 - 40	Elk Provincial Forest	23/11/1968	49-45-26.0	114-41-43.0	Coal waste slide	n	n	Mining

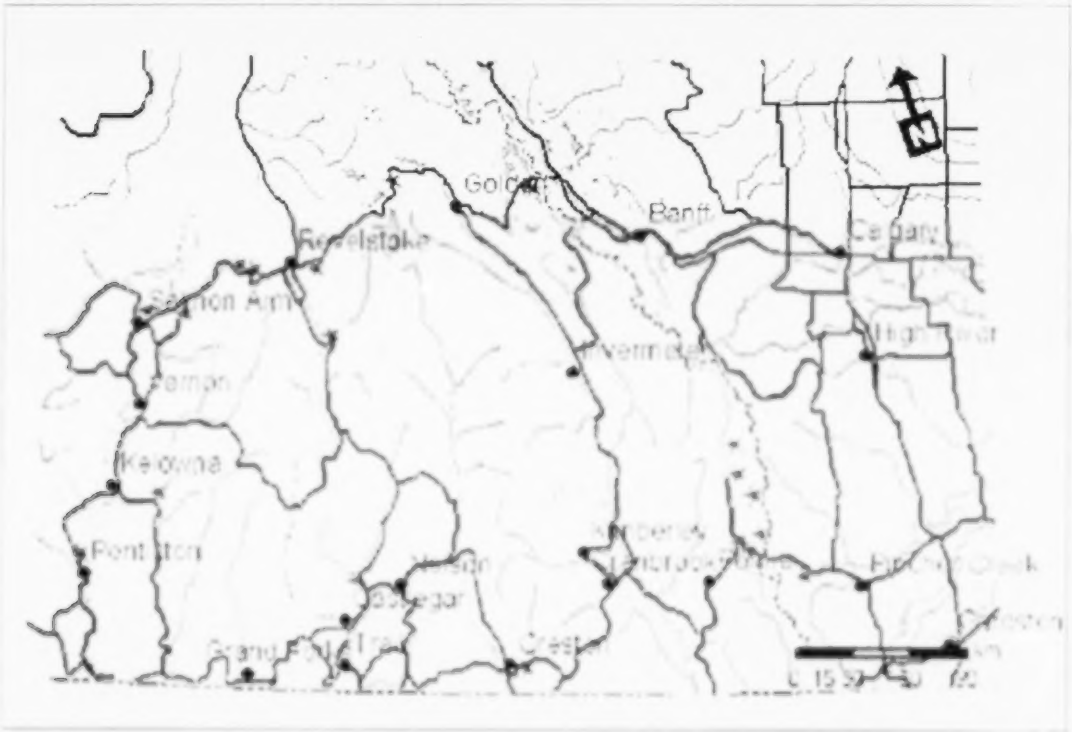
Name of Landslide	Location Name	Date of Occurrence	Latitude (deg.-min.-sec.)	Longitude (deg.-min.-sec.)	Primary Landslide Type	Near Community (y/n)	Presence of Infrastructure (y/n)	Type of Human Activity in Area
Natal	Sparwood	24/11/1968	49-43-27.4	114-51-56.3	Coal waste slide	y	y	Mining
Crescent Valley, Slocan	Nelson	24/03/1969	49-xx-xx	117-xx-xx	Debris flow	n	n	
Summerland	Summerland	27/09/1970	49-36-00.5	119-39-17.4	Silt fall	y	y	Irrigation
WB, North waste dump, Adit 29 - 42	Elk Provincial Forest	05/05/1971	49-45-26.0	114-41-43.0	Coal waste slide	n	n	Mining
WB, KR, Six Mile Creek, Harmer Knob - 43	Elk Provincial Forest	31/05/1971	49-45-26.0	114-41-43.0	Coal waste slide	n	n	Mining
Michel	Sparwood	20/03/1972	49-40-58.4	114-47-03.8	Coal waste slide	y	y	Mining
FCL, Clode spoil piles, Eagle Mountain Project - 19	Elk Provincial Forest	05/05/1972	50-11-20.0	114-53-30.0	Coal waste slide	n	n	Mining
FCL, Clode spoil piles, Eagle Mountain Project - 20	Elk Provincial Forest	27/05/1972	50-11-20.0	114-53-30.0	Coal waste slide	n	n	Mining
WB, 6380 EL, Adit 29S - 44	Elk Provincial Forest	23/05/1973	49-45-26.0	114-41-43.0	Coal waste slide	n	n	Mining
Kelowna	Kelowna	21/06/1974	49-xx-xx	119-xx-xx	Slump	y	n	Irrigation
FCL, Clode waste pile, Eagle Mountain Project - 24	Elk Provincial Forest	08/11/1974	50-11-20.0	114-53-30.0	Coal waste slide	n	n	Mining
FCL, Close waste pile, Eagle Mountain Project - 27	Elk Provincial Forest	12/11/1974	50-11-20.0	114-53-30.0	Coal waste slide	n	n	Mining
WB, South dump, Adit 29 - 38	Elk Provincial Forest	08/02/1976	49-45-26.0	114-41-43.0	Coal waste slide	n	n	Mining
1.5 km north of Vernon	Vernon	28/07/1976	50-14-xx	119-16-xx	Silt fall	y	n	
Spiral Tunnel, Kicking Horse Pass Valley	Yoho National Park	06/09/1978	51-xx-xx	116-xx-xx	Debris flow	n	n	
Beaver Valley	Unknown	07/07/1980			Debris avalanche	n	n	
WB, Bridge 3 dump, Harmer II - 35	Elk Provincial Forest	18/11/1980	49-45-26.0	114-41-43.0	Coal waste slide	n	n	Mining
Trans-Canada Highway, east of Golden	Golden	21/08/1981	51-xx-xx	116-xx-xx	Rock fall	y	y	

Name of Landslide	Location Name	Date of Occurrence	Latitude (deg.-min.-sec.)	Longitude (deg.-min.-sec.)	Primary Landslide Type	Near Community (y/n)	Presence of Infrastructure (y/n)	Type of Human Activity in Area
WB, C1 dump, Adit 40 - 36	Elk Provincial Forest	29/06/1982	49-45-26.0	114-41-43.0	Coal waste slide	n	n	Mining
LCM, West Line Creek, 1996 dump, - 62	Elk Provincial Forest	01/07/1982	49-57-00.0	114-45-20.0	Coal waste slide	n	n	Mining
WB, Greenhills, Hawk Pit dump - 75	Elk Provincial Forest	20/03/1983	50-03-xx	114-52-xx	Coal waste slide	n	n	Mining
WB, Greenhills, 2200 East dump - 76	Elk Provincial Forest	11/05/1983	50-03-xx	114-52-xx	Coal waste slide	n	n	Mining
FCL, Brownie, F gully, Eagle Mountain Project - 162	Elk Provincial Forest	01/06/1983	50-11-20.0	114-53-30.0	Coal waste slide	n	n	Mining
FCL, Brownie East Gully, Eagle Mountain Project - 1	Elk Provincial Forest	11/06/1983	50-11-20.0	114-53-30.0	Coal waste slide	n	n	Mining
Bastion Mountain	Shuswap Highland Provincial Forest	23/11/1983	50-46-42.2	119-15-30.8	Rock fall	y	y	
FCL, Blaine, Spoil 2 - 9	Elk Provincial Forest	30/01/1984	50-11-20.0	114-53-30.0	Coal waste slide	n	n	Mining
FCL, Brownie gully F, Eagle Mountain Project - 5	Elk Provincial Forest	24/07/1984	50-11-20.0	114-53-30.0	Coal waste slide	n	n	Mining
Cathedral Mountain	Yoho National Park	29/08/1984	51-24-30.8	116-23-29.7	Debris flow	n	y	
FCL, Brownie spoil D and E gully, Eagle Mountain Project - 3	Elk Provincial Forest	21/09/1984	50-11-20.0	114-53-30.0	Coal waste slide	n	n	Mining
FCL, Brownie G spoil, Eagle Mountain Project - 7	Elk Provincial Forest	29/06/1985	50-11-20.0	114-53-30.0	Coal waste slide	n	n	Mining
WB, Greenhills, 2100 North dump - 89	Elk Provincial Forest	01/07/1985	50-03-xx	114-52-xx	Coal waste slide	n	n	Mining
FCL, Blackpit spoil, Eagle Mountain Project - 16	Elk Provincial Forest	17/07/1985	50-11-20.0	114-53-30.0	Coal waste slide	n	n	Mining

Name of Landslide	Location Name	Date of Occurrence	Latitude (deg.-min.-sec.)	Longitude (deg.-min.-sec.)	Primary Landslide Type	Near Community (y/n)	Presence of Infrastructure (y/n)	Type of Human Activity in Area
FCL, Brownie B, Eagle Mountain Project - 6	Elk Provincial Forest	16/08/1985	50-11-20.0	114-53-30.0	Coal waste slide	n	n	Mining
FCL, Brownie between G and H gullies, Eagle Mountain Project - 11	Elk Provincial Forest	16/09/1985	50-11-20.0	114-53-30.0	Coal waste slide	n	n	Mining
FCL, Blaine, South spoil - 149	Elk Provincial Forest	16/06/1986	50-11-20.0	114-53-30.0	Coal waste slide	n	n	Mining
WB, Greenhills, 2540 East waste dump - 79	Elk Provincial Forest	12/07/1986	50-03-xx	114-52-xx	Coal waste slide	n	n	Mining
FCL, 13 Seam alternate spoil, Eagle Mountain Project - 12	Elk Provincial Forest	14/08/1986	50-11-20.0	114-53-30.0	Coal waste slide	n	n	Mining
FCL, Blackstone Emergency dump, Eagle Mountain Project - 14	Elk Provincial Forest	05/10/1986	50-11-20.0	114-53-30.0	Coal waste slide	n	n	Mining
WB, Greenhills, 2140 East waste dump - 80	Elk Provincial Forest	12/02/1987	50-03-xx	114-52-xx	Coal waste slide	n	n	Mining
WB, Greenhills, East dump - 81	Elk Provincial Forest	07/03/1987	50-03-xx	114-52-xx	Coal waste slide	n	n	Mining
Penticton	Penticton	11/09/1989	49-xx-xx	119-xx-xx	Debris flow	y	n	
FCL, South spoil - 155	Elk Provincial Forest	26/10/1989	50-11-20.0	114-53-30.0	Coal waste slide	n	n	Mining
WB, Greenhills, 2025 North dump - 156	Elk Provincial Forest	22/11/1989	50-03-xx	114-52-xx	Coal waste slide	n	n	Mining
Kilmarnorck Creek	Elk Provincial Forest	12/12/1989			Coal waste slide	n	n	Mining
FCL, Stage 2 access roadway, South spoil - 153	Elk Provincial Forest	29/05/1990	50-11-20.0	114-53-30.0	Coal waste slide	n	n	Mining
Belgo Creek	Kelowna	12/06/1990	49-55-13.1	119-06-57.5	Planar slide	y	y	Logging
Enderby	Enderby	12/06/1990	50-xx-xx	119-xx-xx	Debris flow	y	y	
Shuswap Mile 22.5	Eagle Provincial Forest	13/06/1990	51-00-47.0	118-34-43.6	Soil slide	n	y	
FCL, Stage 2 access roadway, South spoil - 154	Elk Provincial Forest	07/07/1990	50-11-20.0	114-53-30.0	Coal waste slide	n	n	Mining

Name of Landslide	Location Name	Date of Occurrence	Latitude (deg.-min.-sec.)	Longitude (deg.-min.-sec.)	Primary Landslide Type	Near Community (y/n)	Presence of Infrastructure (y/n)	Type of Human Activity in Area
WB, Greenhills Cougar 7	Elk Provincial Forest	11/05/1992	50-03-xx	114-52-xx	Coal waste slide	n	n	Mining
Summerland	Summerland	15/09/1992	49-36-53.4	119-39-06.0	Silt fall	y	y	Irrigation
Three Valley Gap	Unknown	09/04/1993			Rock fall	y	y	
Kelowna	Kelowna	20/08/1993	49-xx-xx	119-xx-xx	Unknown	n	n	
Kilmarnock Creek	Elk Provincial Forest	12/12/1993	49-xx-xx	119-xx-xx	Coal waste slide	n	n	Mining
Mount Stephen	Yoho National Park	03/08/1994	51-24-58.4	116-26-03.9	Debris flow	n	y	
Kootenay Lake	Nelson	20/01/1995			Rock fall	n	n	
Passmore	Passmore	25/04/1996	49-xx-xx	117-xx-xx	Unknown	y	n	
(near) Sparwood	Sparwood	10/09/1996	49-xx-xx	114-xx-xx	Coal waste slide	n	n	Logging
Winlaw	Nelson	10/10/1996	49-xx-xx	117-xx-xx	Unknown	y	n	
East Gate, Beaver Valley	Glacier National Park	30/01/1997	51-25-53.5	117-26-38.6	Rock topple	n	n	
Creston	Creston	27/03/1997	49-xx-xx	116-xx-xx	Unknown	y	n	
Hummingbird Creek	Eagle Provincial Forest	11/07/1997	50-46-10.1	118-58-12.2	Debris avalanche	y	y	Logging
Goat River Valley	Erickson	31/05/1998	49-08-13.8	116-24-19.7	Flow slide	n	y	Logging
Shuswap Mile 9.5	Eagle Provincial Forest	02/05/1999			Rock slide	n	y	
Five-Mile Creek	Banff National Park	04/08/1999	51-10-45.4	115-39-38.5	Debris flow	n	y	
Slocan Valley	Passmore	13/04/2000	49-32-09.7	117-38-08.8	Flow slide	y	y	
Frank	Frank	03/06/2001	49-33-25.9	114-24-21.1	Rock fall	y	y	Mining
South Columbia River Valley	Edgewater to Canal Flats		50-xx-xx	116-xx-xx	various	y	y	
Ten Mile Hill	Unknown				Unknown	n	n	
Heather Mountain	Glacier National Park		51-25-54	117-26-20	Unknown	n	n	

Figure 4-1 Study area with the locations of landslides that are included in the Damaging Landslide Database



In the database, a main form and six sub-forms were used to present the data. The main form is the Location form, and the sub-forms are Landslide, Landslide Type, Impacts, Causes, Regional Climate, and Documentation. These were thought to best represent the nature of the data captured. These forms and sub-forms were grouped by their jurisdiction.

The main form and the sub-forms usually have a one-to-many relationship (e.g. one location can have many landslides), but in some cases, the forms have a one-to-one relationship (e.g. one landslide has one landslide type). Although the use of another sub-form for a one-to-one relationship is redundant, it was done to better delineate and classify the information. For more information on the Damaging Landslide Database, please contact the authors of this report.

4.1 Analysis of Damaging Landslide Database

The database shows that in the period 1897 to 2001 (105 years), 109 people were killed by landslides in the southeastern Cordillera. Approximately 70 people (65% of the total) were killed in the 1903 Frank Slide, a rock avalanche that buried part of the mining town of Frank, Alberta (see case history in Section 5.1.2). Fourteen people (13% of total) were killed by debris flows or debris avalanches in six events and seven people (6% of total) were killed by failures in built

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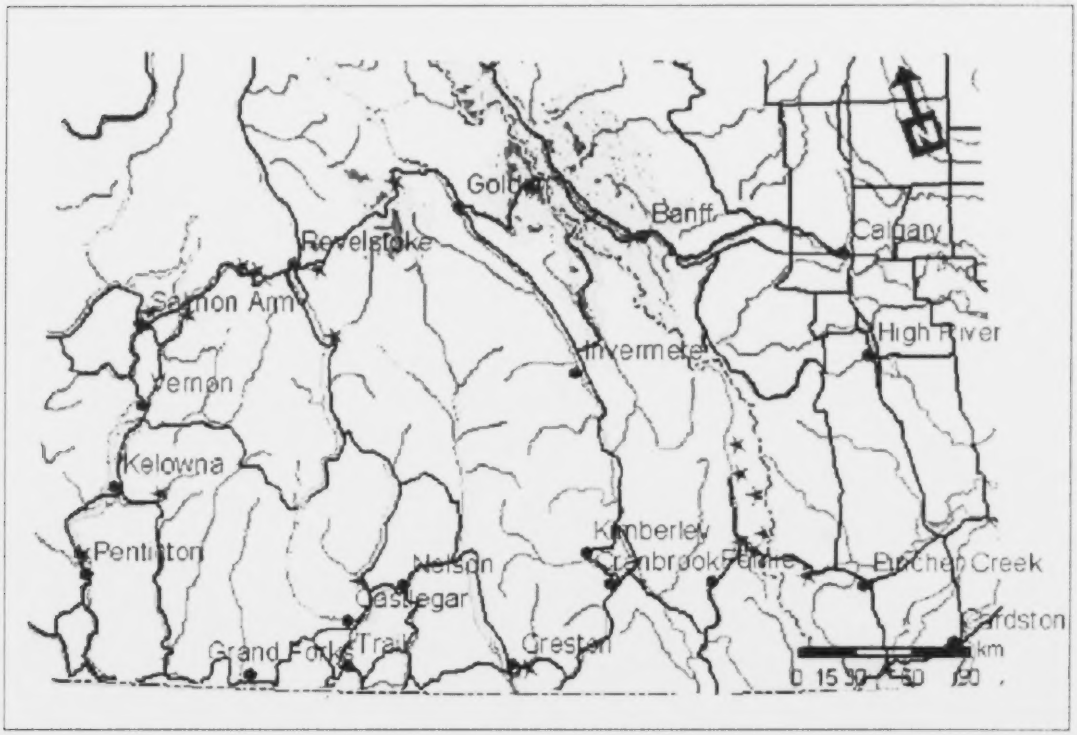

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slopes in three events. Eight people (7% of total) were killed by small rockslides and rockfalls in six events.

A total of 86 landslides are included in the database. The landslide type of nine of these events could not be determined. The other 77 events are considered to be representative of landslides that occur in the region. Coal waste slides were the most common (40; 52%), followed by rapid rainfall-triggered debris flows and debris avalanches (13; 17%), small magnitude rockfalls/rockslides (11; 14%), slides in glacio-lacustrine materials (9; 12%), and siltfalls (4; 5%). Only one rock avalanche is known to have occurred in historical time (the 1903 Frank Slide).

Three events generated significant displacement waves in lakes in the region, buildings were damaged and/or energy and communications lines severed as a result of 12 events, nine landslides caused trail derailments, and 14 events blocked roads.

5.0 Analysis of Damaging Landslide Case Histories

5.1 Landslides Resulting from Rockslope Failure

5.1.1 Rockfall-Generated Wave, Upper Arrow Lake, British Columbia (82K/12); 28 February 1903

At 08:15 on 28 February 1903, a large wave was generated by a rockfall into Upper Arrow Lake, 1.6 km east of Arrowhead, British Columbia (Figures 5-1 and 5-2). The rockfall (estimated volume around 250,000 m^3) initiated from a steep phyllite cliff located about 900 m above the lake surface (Brock, 1904).

Figure 5-1 Sternwheelers docked at the Arrowhead wharf, Arrow Lakes, circa 1898. The wharf was damaged by a rockfall-generated wave in 1903. Sternwheeler *Rossland* (centre) rode out the wave train 11 km from impact (British Columbia Archives Photograph A-00572).

On hitting the lake, the rockfall generated waves up to 3 m high that disturbed the water for one hour and created havoc with shipping on Upper Arrow Lake. During the passage of the wave train, steamers and barges at the Canadian Pacific wharf at Arrowhead (Figure 5-1) were in danger of foundering *(The Weekly News*, Nelson, B.C., 7 March 1903), and piling on the wharf was damaged (*Vancouver Daily Province*, 10 March 1903). Ice at the lake shore was broken up and carried by the wave 18 m inshore.

The force and magnitude of the wave may be illustrated with reference to its effects on four large sternwheelers. The steamer *Kootenay* was at the wharf when the wave struck. The wave lifted the boat over 3.5 m, tearing out the mooring cable. As the steamer came back in the undertow, bow sheeting was wrenched off (*The Weekly News*, Nelson, 7 March 1903). Brock (1904) reports that the *Revelstoke*, a steamer used for towing purposes, was torn from its moorings, thrown onshore and drawn back three times by the waves, while the wreck of the sunken steamer

Nakusp was caught by the wave and whirled around like a chip for several minutes before sinking again (*Vancouver Daily Province*, March 10, 1903; Brock, 1904).

At Albert Point, 11 km to the south (Figure 5-2), the sternwheeler *Rossland* (Figure 5-1) rode out the disturbance (*Vancouver Daily Province*, 10 March 1903) and was not damaged.

Figure 5-2 Location map of 1903 rockfall-generated wave Arrowhead on Upper Arrow Lake, British Columbia. The location of the rockfall is marked by the black arrow. Dock damaged by a landslide-generated wave at Arrowhead (A). Sternwheeler *Rossland* rode out the wave train at Albert Point (circled), 11 km from impact.

5.1.2 Frank Rock Avalanche, Alberta (82G/09); 29 April 1903

The Frank Slide (Figure 5-3) occurred at about 04:10 on 29 April 1903, on the east flank of Turtle Mountain in the southern Rocky Mountains of Alberta (McConnell and Brock, 1904; Daly et al., 1912; Anderson, 1968; Cruden and Beaty, 1987; Kerr, 1990). The rock avalanche began when a rock mass with a volume of about 30 x 10^6 m^3 suddenly broke away from the upper part of the mountain and crashed down its northeast slope (Figure 5-4). The failed mass extended from 270 m to 930 m above the valley floor which is at 1250 m.a.s.l. (metres above sea level). The rapidly disintegrating mass hit the valley floor of the Crowsnest River sweeping across it

and then climbed the opposite terraced slope to a maximum height of 145 m above the river level (Figure 5-3). Some of the debris ran back into the valley.

According to witnesses the whole movement lasted about 100 seconds, but may have been somewhat less (McConnell and Brock, 1904). This indicates an average velocity for the event of about 31 m/s. The shock of the debris hitting the valley floor was distinctly felt by many of the inhabitants of Frank (Kerr, 1990) and the noise of the slide was described as resembling steam escaping under high pressure (McConnell and Brock, 1904). Over 2.5 km of the valley floor was buried by up to 45 m of rock rubble mixed with mud, and the Crowsnest River was blocked by the debris forming a small landslide-dammed lake.

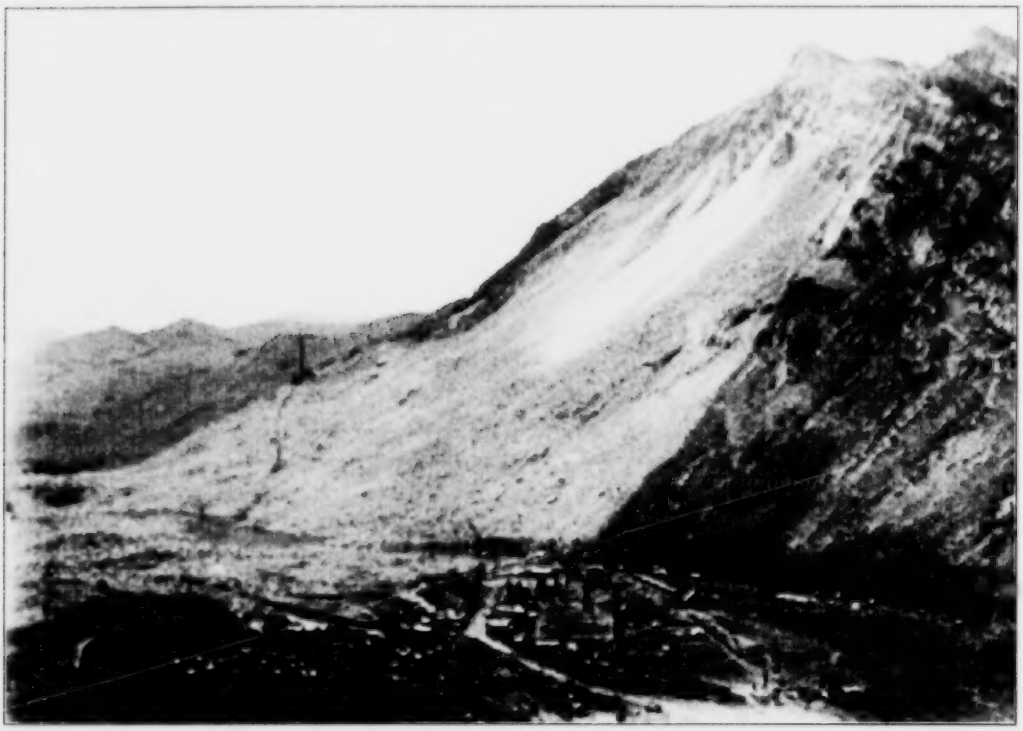
Approximately 70 people perished in the eastern and southern outskirts of Frank in Canada's worst landslide disaster. The loss of life would have been much greater if the slide mass had struck the main part of the town a short distance to the north (Figure 5-4). Property destroyed by the rock avalanche included the tipple (a building where waste rock is removed from the coal and then loaded into railway cars [Kerr, 1990]), sidings and machinery at the mouth of the Canadian American Coal and Coke Company's mine, the company's barns and seven cottages at the east end of the town of Frank, half a dozen outlying houses together with some shacks and camps. The Canadian Pacific Railway was buried for over a distance of more than 2 km, and 1.2 km of a partially completed spur of the Frank and Grassy Mountain Railway was also buried. Much of the damage in the vicinity of Frank itself appears to have resulted from a mud wave, mobilized by the sudden impact undrained loading of sediments in the valley bottom, which was shot out from beneath the rapidly moving debris (Figure 5-5).

Failure involved steeply dipping limestone of the Mississippian Livingstone Formation (Norris, 1989). The base of the failure runs parallel to the fold axis of the Turtle Mountain Anticline (Figure 5-3) and involved strata in the core of the structure above the Turtle Mountain fault. The rock avalanche occurred during a night of extreme cold following a period of spring thaw. Snow still covered parts of the summit ridge.

Figure 5-3 Oblique aerial view of Turtle Mountain and the Frank Slide, Alberta (NAPL T31L-213).

Cracks were known to exist along the crest of Turtle Mountain prior to the landslide (Dowlen, 1903; Burling, 1909). One miner reported that he had to jump over wide cracks in the crown of the mountain when hunting on Turtle Mountain in the fall of 1902 (Blakemore, 1903).

Figure 5-4 View of Turtle Mountain and the Frank Slide shortly after it occurred in 1903 (Glenbow Archives, Calgary, Alberta, Photograph NC-2-355a).



The effect of coal mining at the base of Turtle Mountain, begun in 1901, on the stability of the slope has long been the subject of discussion (e.g., Dowlen, 1903; Daly et al., 1912; Krahn and Morgenstern, 1976; Seager, 1996) but the role of human activity in triggering this catastrophe remains uncertain. However, Daly et al., (1912) concluded that the movement of the mine walls resulting from the extraction of coal was instrumental in weakening the supports of the peak and was possibly directly responsible for the landslide. They further commented that the fact that the part of the mountain which fell in 1903 was exactly opposite to and corresponded in length with the area of large chambers cannot be dismissed as merely a coincidence.

Figure 5-5 Houses destroyed at Frank by mud expelled from beneath rock avalanche debris by impact of debris on valley floor (Glenbow Archives, Calgary, Alberta, Photograph NA-2111-6).

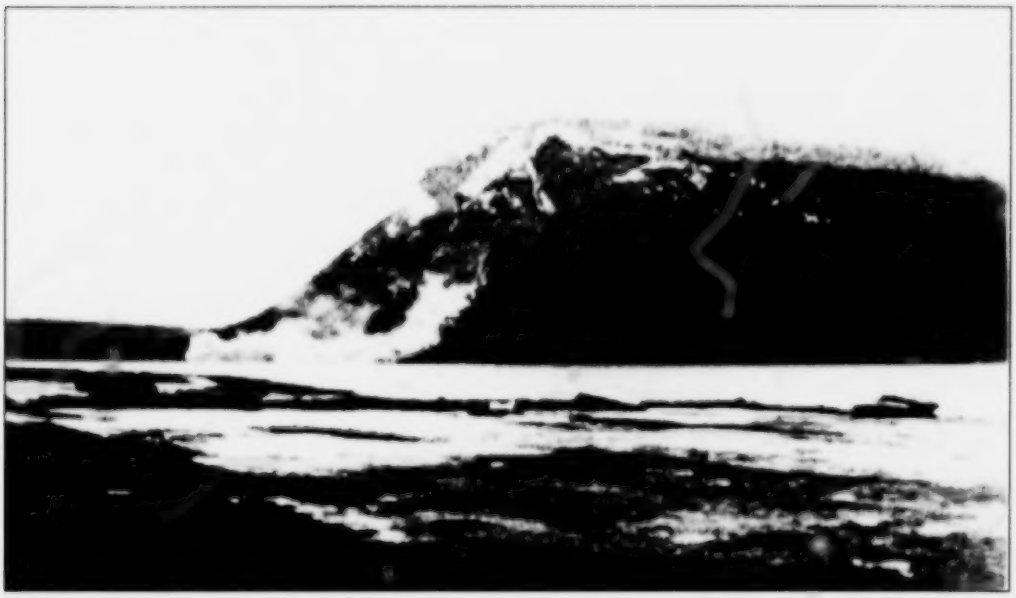
The crown of the Frank slide is currently being monitored for indications of further catastrophic movement (Cruden, 1982a, 1986).

5.1.3 Rockfalls from Bastion Mountain, British Columbia (82L/14); 22 December 1959 and 23 November 1983

Bastion Mountain towers about 900 m above Shuswap Lake, 9 km north of Salmon Arm, British Columbia. The south face of the mountain is a sheer rock wall in Triassic limestone of the Sicamous Formation which has been the source of frequent rockfalls (Evans and Hungr, 1993). Partially vegetated talus slopes skirt the base of the cliff.

One of three rockfalls from the eastern portion of the cliff which occurred on 22 December 1959 was photographed by a local resident (*Vancouver Sun,* 23 December 1959; Figure 5-6). These rockfalls caused no casualties, but in nearby Sunnybrae and Tappen dust from the rockfalls "fell like snow." The rockfalls had been expected for years since a crack in the mountain had begun widening (*Vancouver Sun*, 22 December 1959).

Figure 5-6 Rockfall from Bastion Mountain on 22 December 1959. Shuswap Lake in foreground. View is to the west (photograph courtesy of Mrs. Dorothy Brook).

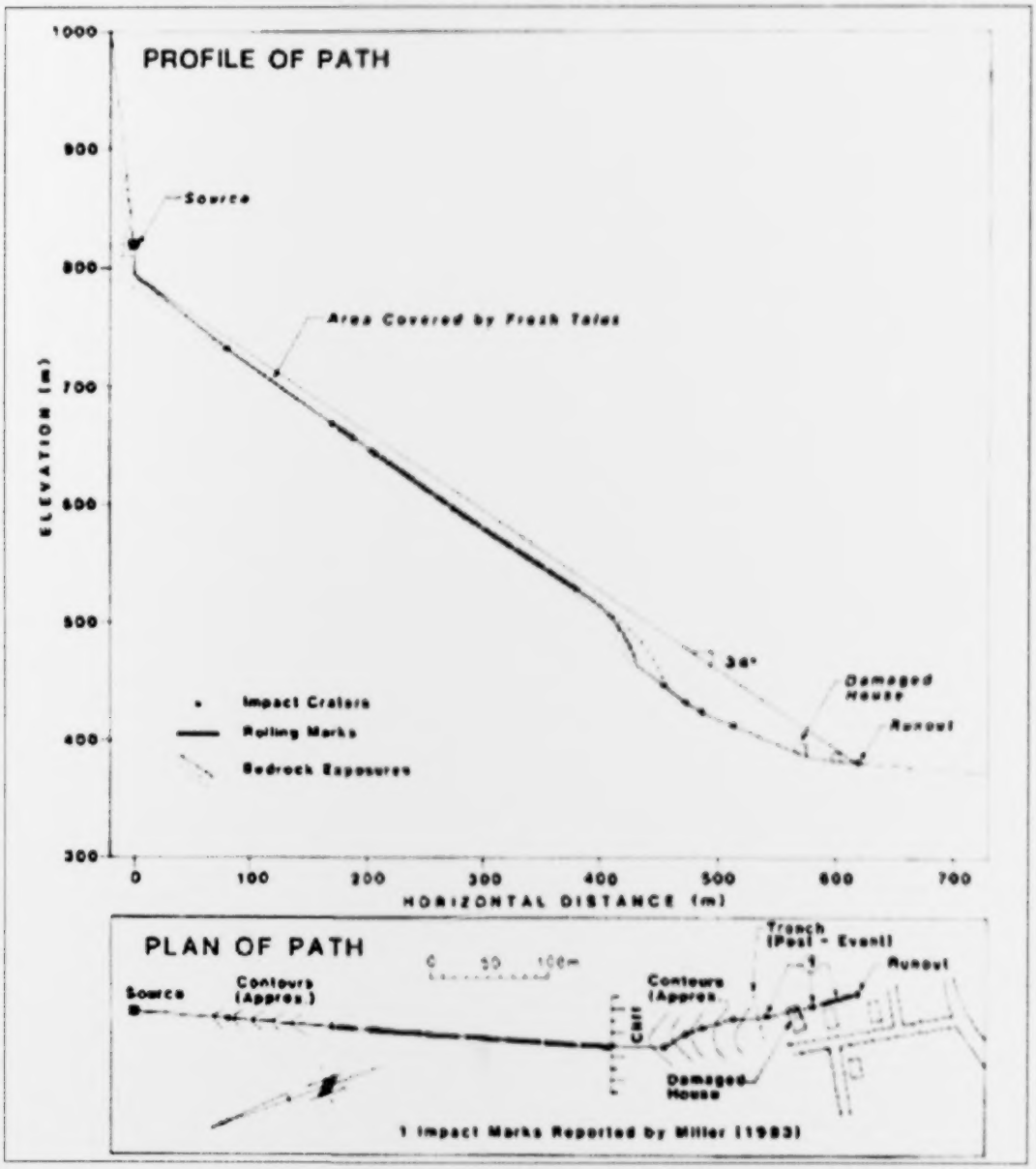


In 1983, however, at 01:50 on November 23, a single, large, wheel-shaped boulder (about 6 m in diameter) broke off the western portion of Bastion Mountain, bounced and rolled down a lightly forested talus slope, and ran out into a residential area on Begbie Road (Hungr and Evans 1988, 1989; Evans and Hungr, 1993; Figure 5-7). Before coming to rest, the boulder, which weighed about 150 tonnes, partially destroyed a house, killing two people while they slept (*Salmon Arm Observer*, 30 November 1983; Figure 5-7).

Figure 5-7 The 1983 Sunnybrae rockfall. Damage to a house on Begbie Road sustained when a boulder smashed through the building. Two people were killed as they slept (British Columbia Ministry of Transportation and Highways photograph, 23 November 1983).

The length of the rockfall path was 750 m in slope distance (Figure 5-8). Miller (1983) reports that a small rock had struck the damaged house in 1982 but caused no significant damage.

Figure 5-8 Path of 1983 Sunnybrae rockfall surveyed in 1987 (after Evans and Hungr, 1993, Figure 18).



5.1.4 Rockfall Along Kootenay Lake, Near Procter, British Columbia (82F/10); 20 January 1995

On 20 January 1995, a CP Rail freight train was derailed when it encountered rockfall debris on the rail track running along the western shore of Kootenay Lake (Figure 5-9). Three locomotives and two freight cars left the track and plummeted 30 m down a cliff face into the waters of Kootenay Lake (Figure 5-9). Two trainmen were killed in the plunge (Transportation Safety Board, 1995).

The rock making up the slope at the rockfall site is a strong, well-jointed granite of the Heather Creek pluton (Leclair, 1986). The direction of initial movement of the rockfall was between 50E and 62NE. The rock fabric and the cut slope geometry at the site are conducive for block toppling, which is thought to be the most likely mechanism of detachment. The rockfall had an estimated volume of 144 m^3 (Transportation Safety Board, 1995).

Climate data indicate that the rockfall was triggered by the onset of freezing conditions after an 11 day thawing period which followed a very cold start to the month of January. Rain had fallen during the thaw period as well, adding to the water available to freeze in spaces (cracks or open joints) in the rock mass.

The case history illustrates the destructive impact of a relatively small rockfall and is typical of rockfall incidents that have occurred from time to time in the life of the railway system in the southeastern Cordillera.

Figure 5-9 Aerial overview of rockfall site and derailment scene taken on 20 January 1995. Note steep rock slopes from top of cut down to lake level controlled by steeply dipping joints. North is to the right (RCMP photograph).

5.1.5 Rockslides in the Beaver River Valley and the East Gate Landslide, Glacier National Park, British Columbia

Mountain slope movements have been recognized at numerous sites in Glacier National Park (GNP), British Columbia. This part of the Columbia Mountains is characterized by glacially over-deepened valleys and steep mountain slopes underlain by structurally complex metamorphic rocks; the landscape is especially prone to major slope movements.

The Beaver River Valley forms the eastern approach to Rogers Pass and is particularly affected by deep-seated slope movements. Several slope movements have been investigated (e.g., Pritchard et al., 1989; Pritchard & Savigny, 1991; Couture & Evans, 2000b). Large deep-seated landslides on the Beaver River Valley slopes cause maintenance problems on both the Canadian Pacific Railway and the Trans-Canada Highway.

Most of the landslides in the Beaver Valley have occurred on its eastern slopes and have taken place in the grit and slate division of the Pre-Cambrian Horsethief Creek Group. Many landslides are visible on aerial photographs and are outlined on the 1999 air photo and topographic map in Figure 5-10. The slope deformations are recognizable by the hummocky broken terrain as opposed to the smooth surface of adjacent undisturbed slopes. The footprint left by those slope deformations varies in size from about 0.25 km^2 to 5 km^2. These zones of post-glacial slope movements are deep-seated landslides showing bowl-shaped features with a semi-circular head scarp and bulging toes.

On the western flanks of the Beaver River Valley, at least six mass movements were identified (Pritchard et al., 1989; Pritchard & Savigny, 1990). At Griffith Slide, progressive deformations generating movement of the debris and causing displacement of the CPR line throughout its life have long been measured. Pritchard et al. (1989) reported results of slope monitoring that indicated deformations of up to approximately 30 mm over a one-month monitoring period. Previously identified as a circular mode of failure, Griffith Slide is now recognized as the final stages of an earlier massive toppling failure (Pritchard et al., 1989).

The Heather Hill landslide (Figure 5-10) is located on the eastern slopes of the Beaver River Valley. Field evidence, kinematics analysis, as well as numerical modeling, confirmed toppling deformation as a principal failure mechanism that limits to a curvilinear failure surface (Pritchard & Savigny, 1990; Pritchard & Savigny, 1991).

With respect to the East Gate landslide (Figure 5-11), in late May 1999, mudslide debris covered the Trans-Canada Highway 1.5 km north of the East Gate of Glacier National Park in the Beaver Valley. The debris originated from disintegrating rockslide debris that occurred two years before high above the highway in an area of active rock slope failure (Couture and Evans, 2000b, 2002) now known as the East Gate landslide. In January 1997, a reactivation of a very large post-glacial landslide was brought to the attention of Glacier National Park authorities. The current landslide involves retrogressive bedrock failures on an over-steepened head scarp involving rocks of the Pre-Cambrian (Figure 5-11). During a relatively short period of time (about 28 months), debris generated by disintegration of bedrock slumps has moved down the mountain slope a distance of 3.4 km. A small amount of debris reached the highway in late May 1999 (Figure 5-11), fortunately without any disastrous consequences. In the following weeks and

months, the slump block had slightly disintegrated and moved downslope. By early June 1999, National Parks highway maintenance crews had cleared about 6000 m^3 of debris off the Trans-Canada Highway; at the end of July 15,000 m^3 had been removed.

Since 1999, debris flows have occurred every year during the snow-melting period, usually during May and June. Debris flows at the East Gate landslide are strongly influenced by the hydrological conditions in the slope, and unfavourable weather conditions could generate larger debris flows than those experienced to date.

A barrier berm and debris basin have been constructed just above the Trans-Canada Highway to protect it from debris flows originating in the East Gate landslide debris above.

Figure 5-10 Aerial view of the bottom part of the East Gate landslide (upper right). Trans-Canada Highway runs at the base of the slope, above the Beaver River. Note berm and catch basin constructed above the Trans-Canada Highway to protect the highway from debris flows originating in the East Gate landslide debris. Heather Hill landslide is visible top left and Soup Kitchen instability can be seen to the right of the berm works, just above the Trans-Canada Highway (photograph by S. G. Evans, August 2002).

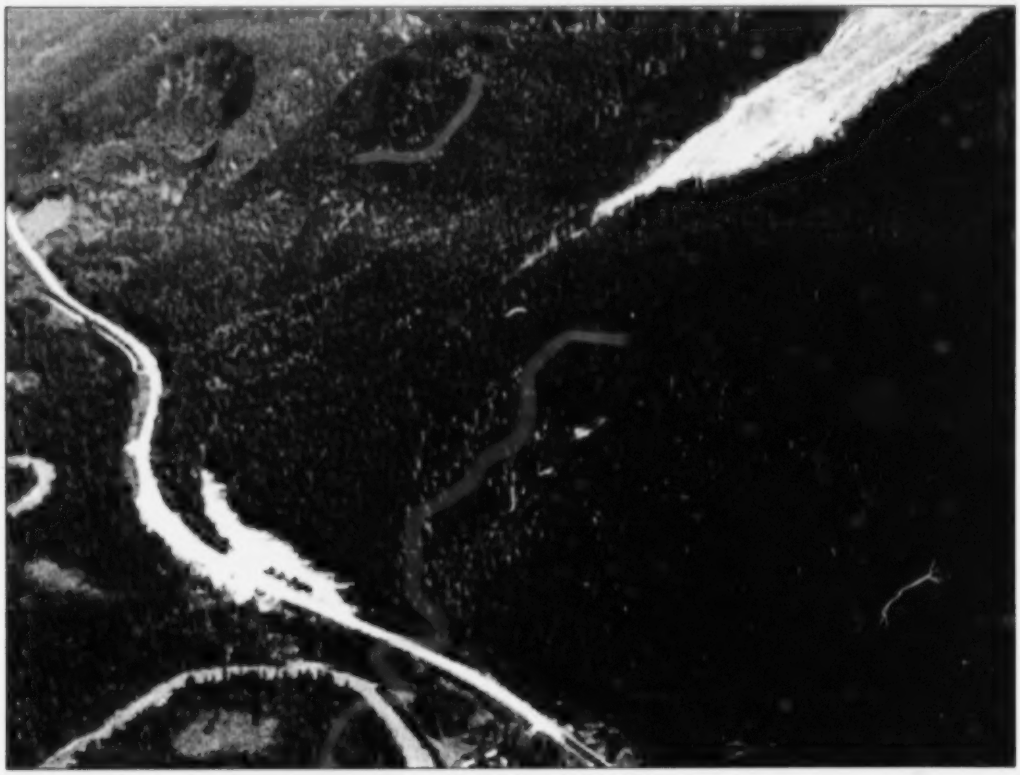


Figure 5–11 a) 1:30,000 scale aerial photograph (Foto-Flight, 1999, #99043-L1-3), and b) 1:50,000 scale topographic map (NTS # 82/N-6) of Beaver River valley in the vicinity of East Gate Landslide (EGL). Limits of ancient and recent slope failures are sketched on both images. **BB**: Beaver Berms debris flows area; **HH**: Heather Hill Landslide; **SK**: Soup Kitchen debris flows area. Note: contour interval on topographic map = 100 feet (33.3 m) (from Couture & Evans, 2000b).

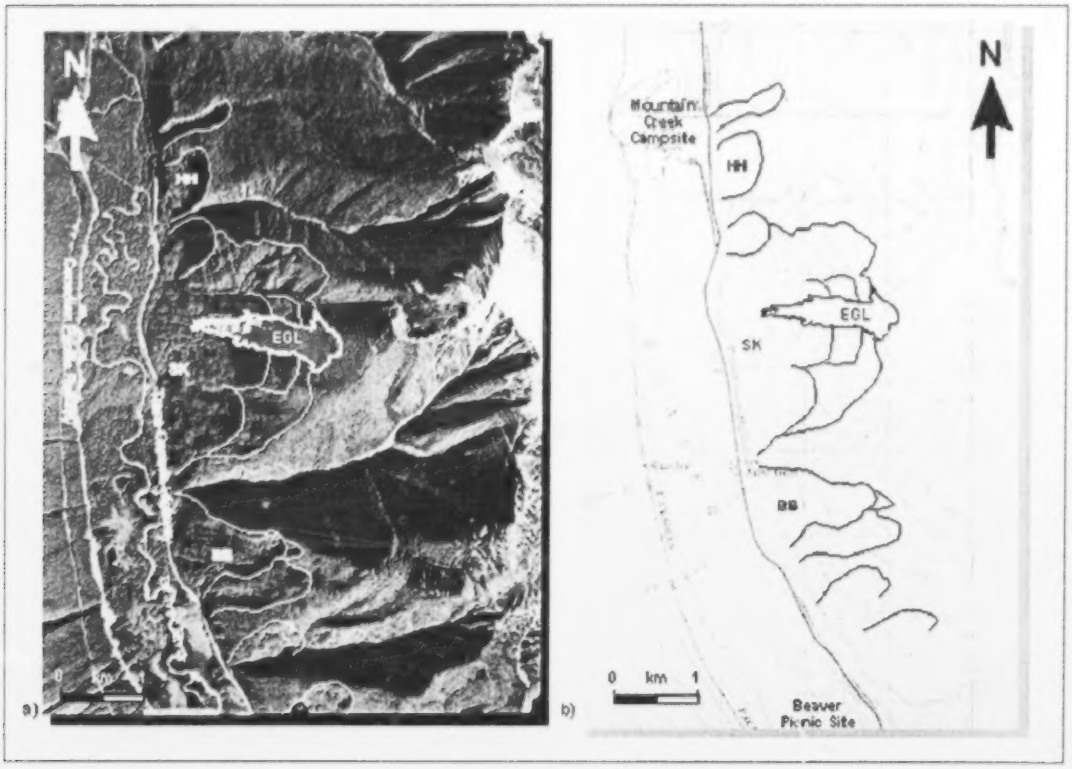
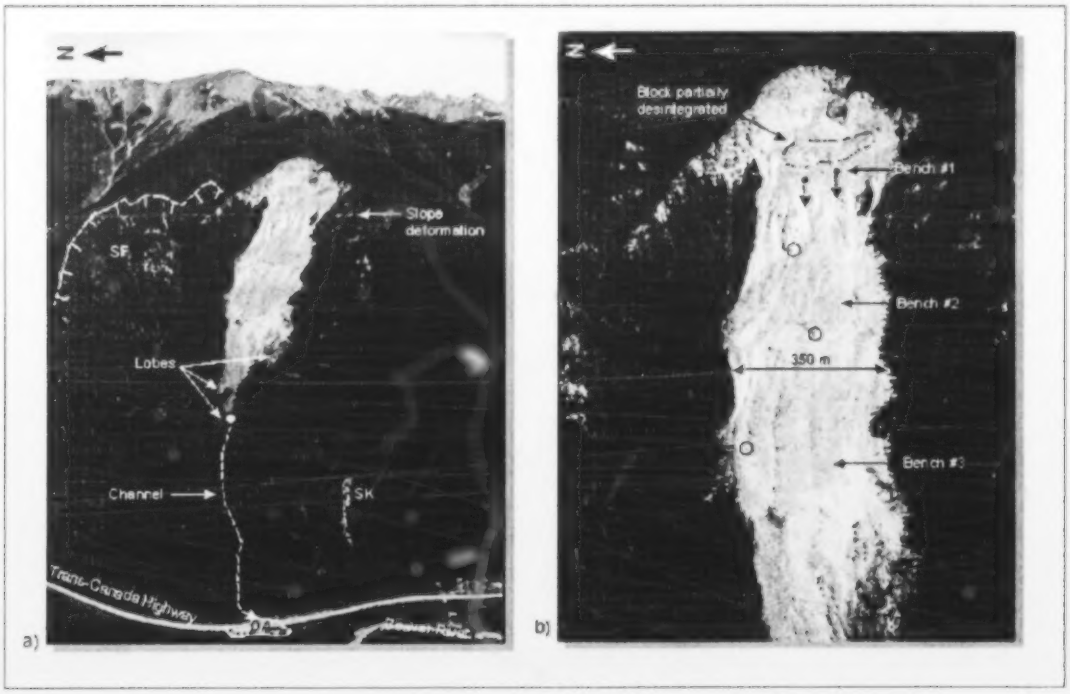


Figure 5–12 a) Oblique aerial view of the East Gate landslide. Slope deformation is identified on the southern slopes of the landslide head scarp (SF); b) Close-up of the upper part of the East Gate landslide. Three zones of debris accumulation, identified as benches #1 to #3, show permanent and slow downslope displacements. A few large blocks can be identified at the level of bench #2 and bench #3 (circled). DA: Deposition area of the 1999 debris flow; SK: Soup Kitchen debris flow area (from Couture & Evans, 2000b).



5.1.6 Clanwilliam Rockslide-Debris Avalanche, Eagle Pass, Columbia Mountains, British Columbia, May 1999

In May 1999, a rockslide-debris avalanche took place in the northern part of the Monashee Mountains about 15 km west of Revelstoke along the Canadian Pacific Railway/Trans-Canada Highway corridor (Figure 5-13). Part of the debris impacted the Canadian Pacific Railway (CPR) track, resulting in a temporary halt in train traffic. Most of the debris was deposited on the slope where the railway runs through a tunnel at the base of the slope (Figure 5-13). The rockslide-debris avalanche did not affect the Trans-Canada Highway, located on the opposite side of the valley.

The volume of rock that detached from the source cliff, 470 m above the valley floor, is estimated to be 75,000 m^3. This volume was increased by entrainment of colluvium in its path. The initial rockslide involved gneiss of the Lower Paleozoic Monashee Complex (Johnson, 1990). The Complex typically consists of schist, quartzite, marble, and para and ortho gneiss;

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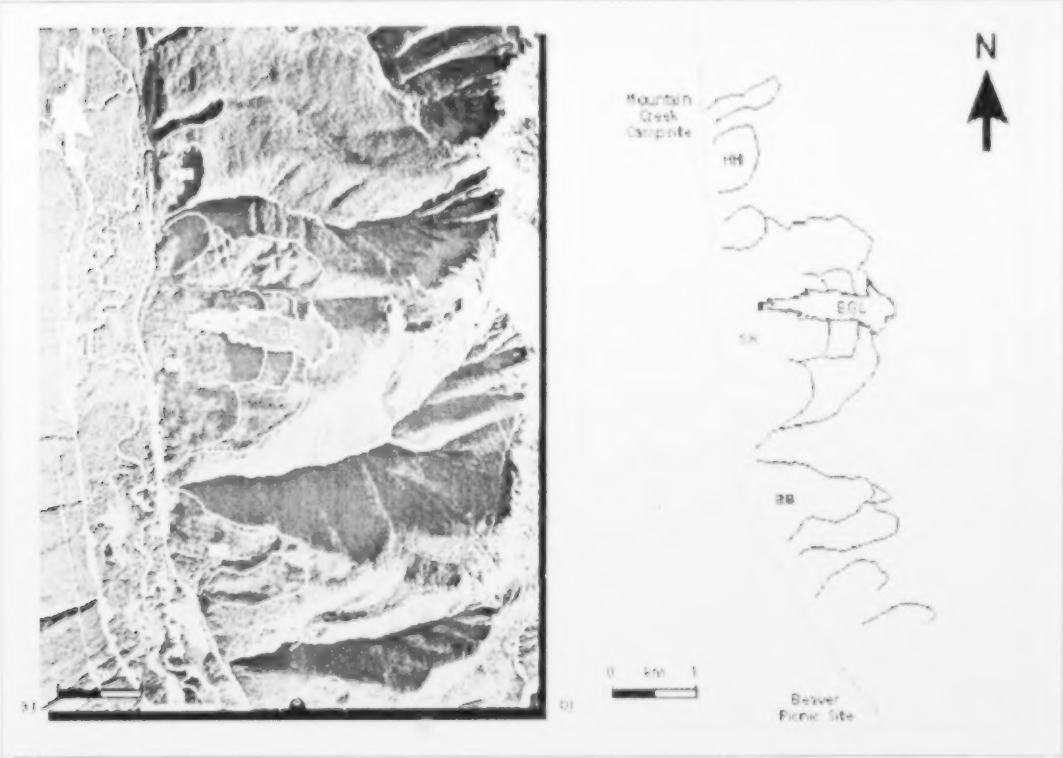

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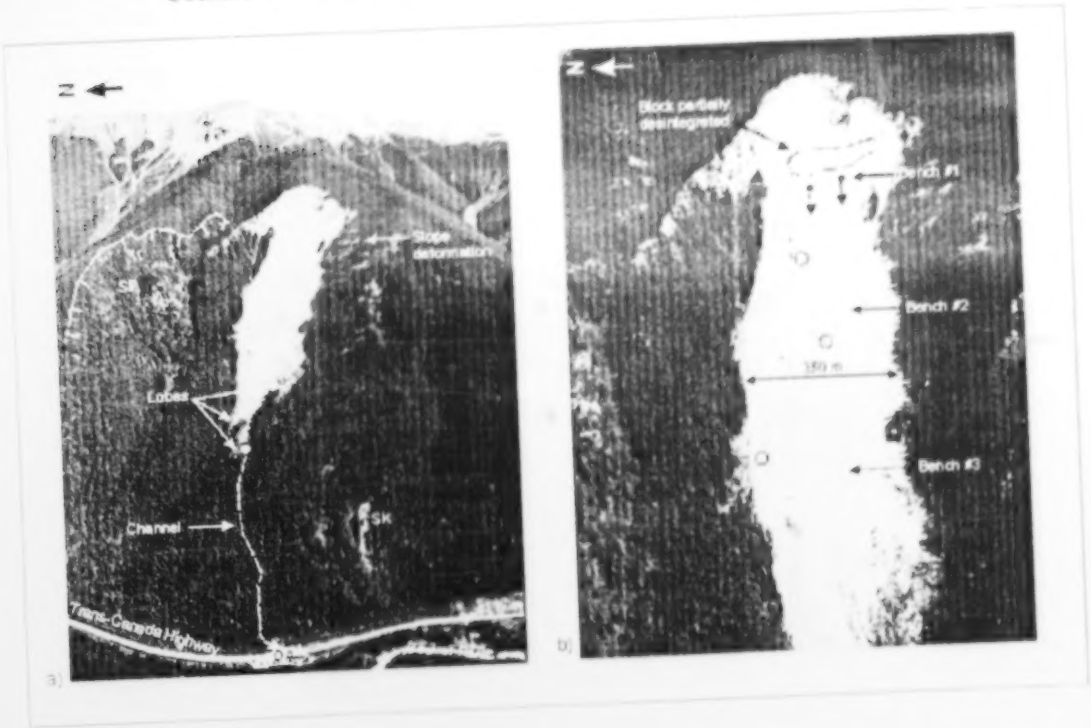

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foliation and schistosity strike NW-SE (N135°) and dips about 37° SW. Post-failure dynamic analysis of the rock avalanche found that the velocity of the debris avalanche phase of the movement reached 30 m/s (Hungr et al., 2000).

Figure 5-13 Oblique aerial view of the Shuswap Mile 9.5 rockslide-rock avalanche located near Clan William Lake on the northern slopes of the Eagle River valley, Eagle Pass. CP Railway track runs at the base of the slope and runs through a tunnel where the debris reached the base of the slope (photograph by R. Couture, August 1999).

5.2 Debris Flows and Debris Avalanches

5.2.1 Little Sheep Creek Debris Flow, Near Rossland, British Columbia (82F/04); 20 April 1897

A debris flow struck a railway maintenance camp, consisting of a cook house, bunkhouse, and several tents, at 02:20, 20 April 1897 on the Red Mountain Railway, along Little Sheep Creek 1.6 km north of the International Border, near Rossland, British Columbia (*Daily Colonist*, 21–22 April 1897). The 12 members of the railway gang were sound asleep when they were awoken by the noise of the debris flow, a rumbling sound which one of the survivors took to be "a (railway) car off the track and bumping along the ties." Seven of the gang were killed, four survived after being buried in the debris, and one person escaped uninjured. The debris flow was quite large and had an estimated volume of over 50,000 m^3 (*Rossland Weekly Miner*, 22 April 1897).

5.2.2 Twin Butte Debris Flow, Illecillewaet Valley, Near Revelstoke (82N/04-82M/01); 11 May 1961

At about 20:30 on 11 May 1961, a CPR freight train travelling west in the Illecillewaet Valley toward Revelstoke collided with a debris flow at Twin Butte. Four diesel locomotives and 18 boxcars carrying wheat from the Prairies and destined for Vancouver were derailed. No one was hurt in the accident. The incident is of considerable interest because of subsequent litigation in which the Wheat Board (Her Majesty the Queen) claimed damages from Canadian Pacific Railway for failing to deliver the wheat to Vancouver. These proceedings are summarized in a 1965 Exchequer Court of Canada ruling, and contain illuminating insights into the assessment of landslide hazard and the acceptance of risk.

The debris flow occurred in a steep watershed on the south side of the Illecillewaet valley at Mile 116.5 of the CPR's Mountain Sub-division. Debris covered the tracks for about 30 m up to a depth of 3 m. The debris flow had occurred less than three hours before the train's arrival. No rain had fallen on that day nor for some time before the incident. The debris flow was thought to have originated in a debris slide well above the track. The slide blocked the stream and the subsequent breach of the blockage triggered the May 11 debris flow. Other slides had occurred in the steep watershed and were visible on aerial photographs, a fact which became an important point of evidence in the case.

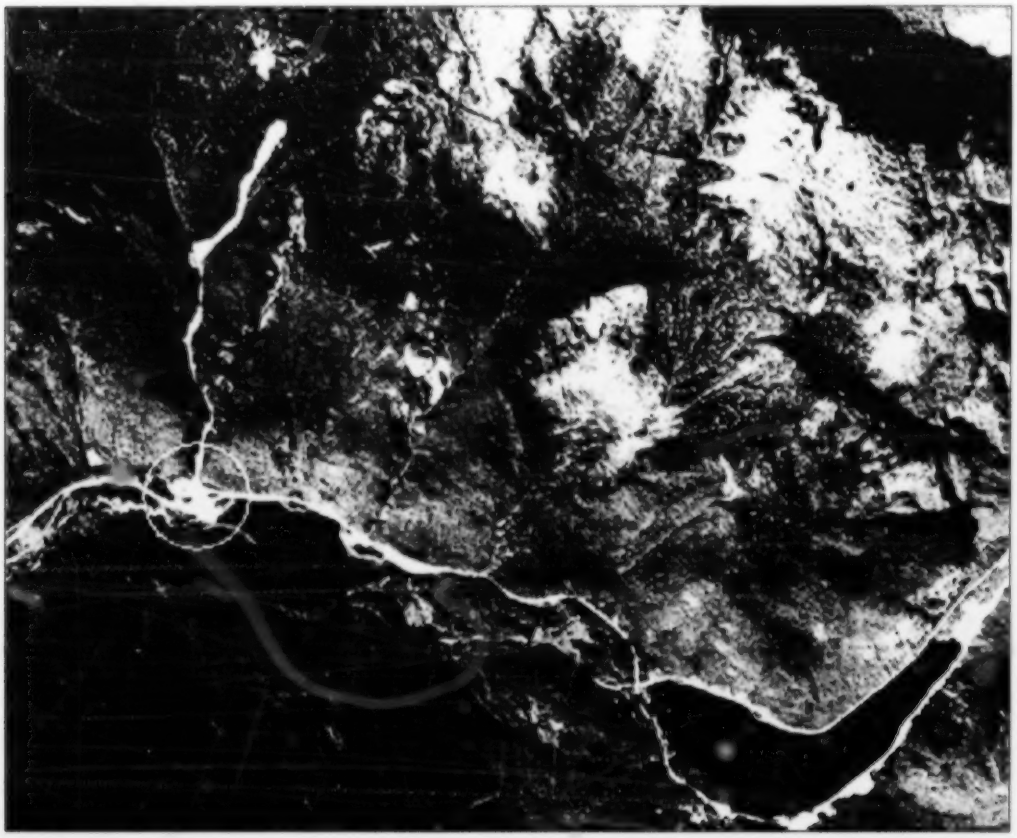
In his judgement Hon. Mr. Justice Dumoulin dismissed the defendant's argument that the debris flow was an "Act of God...which... could not have been foreseen and which could not be guarded against" and awarded the Wheat Board the sum of $46,199.95 (1965 dollars), the value of the spoiled wheat. The total cost of the 1961 derailment to CPR, including repairs to diesel engines, rolling stock, rails, and signals amounted to $130,000 (1961 dollars). A warning fence was set up at Mile 116.5 to protect the railway after the 1961 debris flow.

A similar incident had taken place at Mile 86.7 on 24 June 1958 when another freight train had collided with a debris flow resulting in the derailment of four diesel engines and 10 cars containing wheat. In that case the Exchequer Court of Canada allowed the Plaintiff's action for $32,655.12 (1958 dollars).

5.2.3 Camp Creek Debris Flow, British Columbia (82L/15–16); 5 June 1968

At about 15:30 on 5 June 1968, a massive debris flow in Camp Creek (estimated volume about 75,000 m^3 (Nasmith, 1972)), engulfed a car travelling west on the Trans-Canada Highway, 29 km west of Revelstoke, British Columbia (Figure 5-14). The debris flow killed four members of a family travelling in the car and a fifth, a six-year old child, was found alive sitting on top of the debris (*Vancouver Sun*, 6 June 1968). Debris flowed over the Camp Creek bridge and the Trans-Canada Highway at the northwest end of Griffin Lake, blocking the highway for two days. Debris covered the highway up to 6 m deep and included a huge boulder 4 m in diameter.

Figure 5-14 Aerial photograph Camp Creek debris flow showing initiating debris avalanche, super-elevation of debris at stream junction, and winding path to the Trans-Canada Highway. Location of impact on the Trans-Canada Highway at west end of Griffin Lake is circled at left (National Air Photo Library A 23011; 119-118).



The debris flow originated as a 10 m deep debris slide in thick glacial till at an elevation of 1675 m on a steep forested slope, 1240 m above and 3.5 km northeast of the Trans-Canada Highway. The slide was transformed into a mobile debris flow that swept down Camp Creek, picking up large amounts of debris from the creek bed. The debris showed dramatic super-

elevation going through a bend at 1066 m.a.s.l. (Figure 5-14). The flow moved rapidly (estimated at about 8 m/s) while confined to the steep creek valley, but quickly came to rest when it spread across the Camp Creek fan. The debris flow was preceded by heavy rains and warm weather which caused rapid snowmelt in the upper reaches of Camp Creek (unpublished British Columbia Ministry of Transportation and Highways records).

In June 1990, to the west of Camp Creek a westbound CN Train, travelling on the CPR track near Mile 22.50 Shuswap Subdivision, struck a debris flow and derailed 14 cars. The main line was out of service for approximately 21 hours. The debris flow was triggered by heavy rainfall. Approximately 4,600 m^3 of debris reached the track.

5.2.4 Cathedral Mountain Debris Flows, Kicking Horse Valley (82N/08); 6 September 1978 and 29 August 1984

Debris flows from the north side of Cathedral Mountain, 6.5 km northeast of Field, in the Kicking Horse valley have periodically disrupted road and rail traffic through the valley since at least 1925 (Jackson, 1979; Jackson et al., 1989). Two major events took place in 1978 and 1984.

1978: At approximately 21:00 on 6 September 1978, both the Canadian Pacific Railway and the Trans-Canada Highway were buried by a debris flow in the vicinity of Spiral Tunnels, Kicking Horse Valley. A total of 175,000 m^3 of debris was deposited, and the flow partially buried the locomotives of a freight train (Jackson, 1979) (Figure 5-15). The velocity of the main surge was estimated to be about 6 m/s.

Figure 5-15 Aerial oblique photograph of September 1978 debris flow at Cathedral Mountain showing eastbound freight train caught in debris flow. View is to the east. Debris also covers the Trans-Canada Highway at upper left (Glenbow Archives photograph CH-17A).

Figure 5-16 Aerial oblique view of the Cathedral Mountain debris flow track. Debris flows are triggered by periodic water release events from Cathedral Glacier (arrowed). Note the three levels of track associated with the Spiral Tunnels. View in Figure 5-15 of 1978 debris flow is circled. Trans-Canada Highway also runs left to right in foreground (photograph by S.G. Evans, September 1997).

1984 : Between 08:30 and 10:00 on 29 August 1984, debris covered the upper two CPR tracks and flowed onto the Trans-Canada Highway (Figure 5-16). The volume was an order of magnitude less (estimated volume 90,000m^3) than the 1978 event and traffic was restored in about 28 hours. Estimated maximum velocity in the debris flow path was 5.5 m/s (Jackson et al., 1989).

The debris flows were initiated by the sudden drainage (jokulhlaup) of at least 10,000 m^3 and perhaps as much as 24,000 m^3 of water from Cathedral Glacier, about 1500 m above the valley (Jackson et al., 1989). The floodwaters incorporated debris from the bed and walls of Cathedral Gulch in their passage down to the Kicking Horse Valley floor. Similar debris flows generated by jokulhlaups from Cathedral Glacier buried the Canadian Pacific Railway tracks in 1925 and 1946.

No debris flows have occurred since the implementation of jokulhlaup abatement measures described by Jackson et al. (1989).

5.2.5 Belgo Creek Debris Avalanche, Joe Rich District, British Columbia (82E/14); 12 June 1990

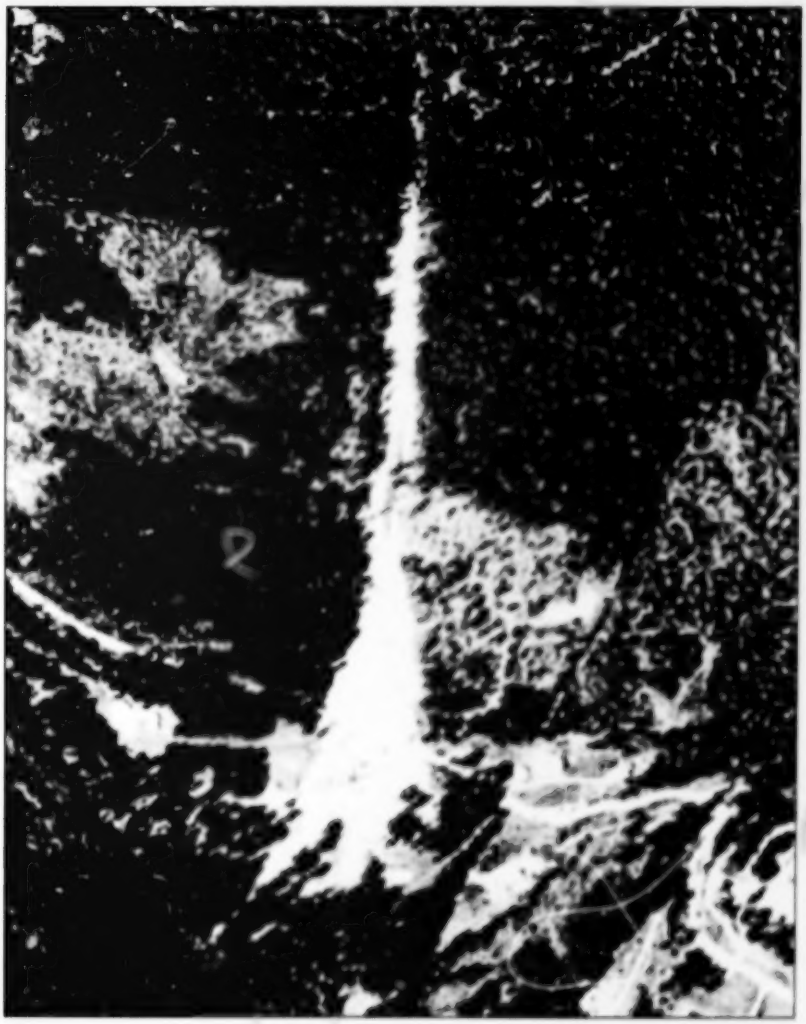
At about 14:30 on 12 June 1990, a debris avalanche travelled 830 m down the west side of the Belgo Creek valley, in the Joe Rich District, about 30 km east of Kelowna, British Columbia (Figure 5-17; Cass et al., 1992; *The Vancouver Sun*, 13–14 June 1990; Hungr, 1997a). The landslide, which was accompanied by a loud roar, demolished a house and outbuildings on Philpott Road, and buried two cars. Three occupants of the house lost their lives.

The debris avalanche began as a small planar slide of a thin layer of colluvium over gneissic bedrock on a slope of 33 degrees at 1215 m.a.s.l. (Forest Service Investigative Team, 1990; Hungr, 1997a). The colluvium consisted of 45% sand, 35% silt, 10% clay, and 10% organic matter. Debris from the initial slide rapidly moved downslope overriding the saturated colluvial veneer below it. A debris avalanche quickly developed by the entrainment of saturated colluvium in its widening path, and grew rapidly in volume. Hungr (1997a) suggests that undrained loading of the overridden surface layer was an important process in the entrainment of material on the slope as the debris avalanche developed. The deposition zone was downslope of the sharp change in slope at 925 m.a.s.l. at which point the width of the debris avalanche was 150 m. The house was impacted in this zone.

The velocity of the avalanche, which involved about 23,000 m^3 of debris, was estimated to be 10 m/s (Cass et al., 1992). Estimates of super-elevation in curving segments of the debris path indicate a local velocity range of 15–20 m/s (Hungr, 1997a).

The event occurred on a hillside with no previous record of slope failure (Figure 5-17). However, three other landslides occurred to the south on the same slope the day before the main slide took place. Logging of the terrain above the site was found to be a contributing cause of the landslide (*The Province*, 2 August 1990). The avalanche was triggered by intense rains, combined with rapid snow melt; the 42 day period prior to the landslide was the wettest on record (Cass et al., 1992). Numerous other debris flows and avalanches were triggered in the B.C. Interior by the heavy rains of this period (Cass et al., 1992).

Figure 5-17 Aerial photograph of 1990 Belgo Creek debris avalanche site taken on 2 August 1993 (Province of British Columbia 30BCC93061; 12).



5.2.6 Mount Stephen Debris Flow, Near Field, British Columbia (82N/08); August 3, 1994

The Mount Stephen debris flow track (Figure 5-18), located 4.5 km northeast of Field, British Columbia has been subject to periodic debris flow and snow avalanche activity which has impacted on the CP Rail mainline on several occasions in the past. In July 1937, a passenger train escaped serious damage only by outrunning a massive debris flow (*Calgary Herald*, 29 July 1937) which may have had a volume of 110,000 m^3 (Thurber Engineering, 1994). In 1985 a snow avalanche down the same path struck a freight train resulting in the derailment of 15 cars. The debris flow track was created in this century by the erosion of a debris cone (Figure 5-18),

possibly following the melting of a permafrost cap at its apex associated with regional climate warming (Thurber Engineering, 1994).

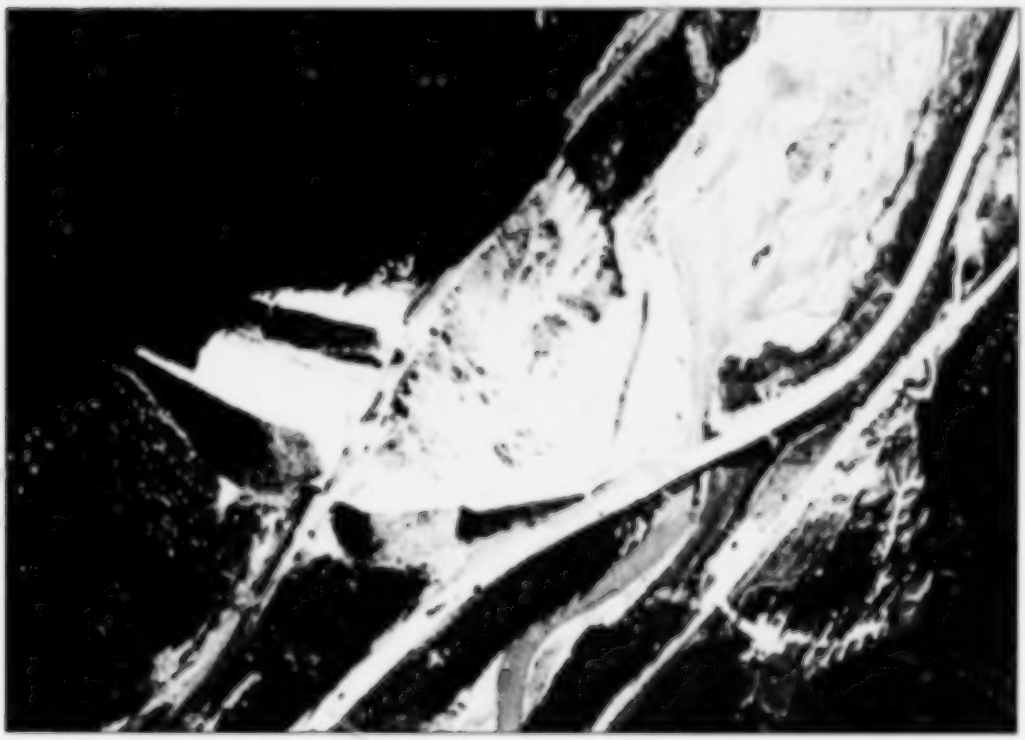
In 1987, CP Rail constructed a defensive structure, consisting of a concrete shed and an upstream curving deflector dyke, to protect the railway from debris flows and snow avalanches (Fig. 5-19; Hungr et al., 1987). A marginal dyke was also constructed in the runout area to deflect the debris parallel to the Trans-Canada Highway embankment (Figure 5-19; *Calgary Herald*, 28 August 1994). Following completion of the works, three debris flows occurred in 1988, 1989, and 1994, and were successfully passed over the railway by the concrete shed.

Figure 5-18 Oblique aerial view of Mount Stephen (3185 m.a.s.l.) and the debris flow track (partly in shadow) beneath the hanging glacier. Note channelisation works above the CP Rail track which passes under the debris flow/avalanche shed (track is at 1330 m.a.s.l. in shed), Trans-Canada Highway, and Kicking Horse River (approximate 1265 m.a.sl.) flowing to the right (photograph by S. G. Evans, May 2000).

The debris flow of 3 August 1994, consisted of debris mobilized from the cone by a very intense thunderstorm in the late afternoon. The debris flow had an estimated volume of 42,000 m^3 and split into two tongues after passing over the shed, one of which flowed along the foot of the Trans-Canada Highway embankment, beyond the end of the marginal dyke, and entered the Kicking Horse River (Thurber Engineering, 1994). The terminus of this flow tongue deposited several thousands of cubic metres in the channel of the river, damming the channel and causing an avulsion upstream. This caused the flooding and partial erosion of the Trans-Canada Highway west of the bridge resulting in its closure for about 24 hours, and the temporary closing of a National Parks campsite (*Vancouver Sun*, 5 August 1994).

In the fall of 1994, a 4.5 m high terminal dyke was constructed in the depositional area below the railway in order to reduce the future impacts of debris flows on the Kicking Horse river (Figure 5-19).

Figure 5-19 Oblique aerial view of debris flow / snow avalanche protective and containment structures constructed in the run-out zone of the Mount Stephen debris flow track. These consist of channelisation works upslope of rail track, debris flow / snow avalanche shed, and marginal dyke to protect the Trans-Canada Highway. Note the terminal dyke constructed in 1994 to prevent debris flows from entering Kicking Horse River (photograph by S. G. Evans, September 1997).



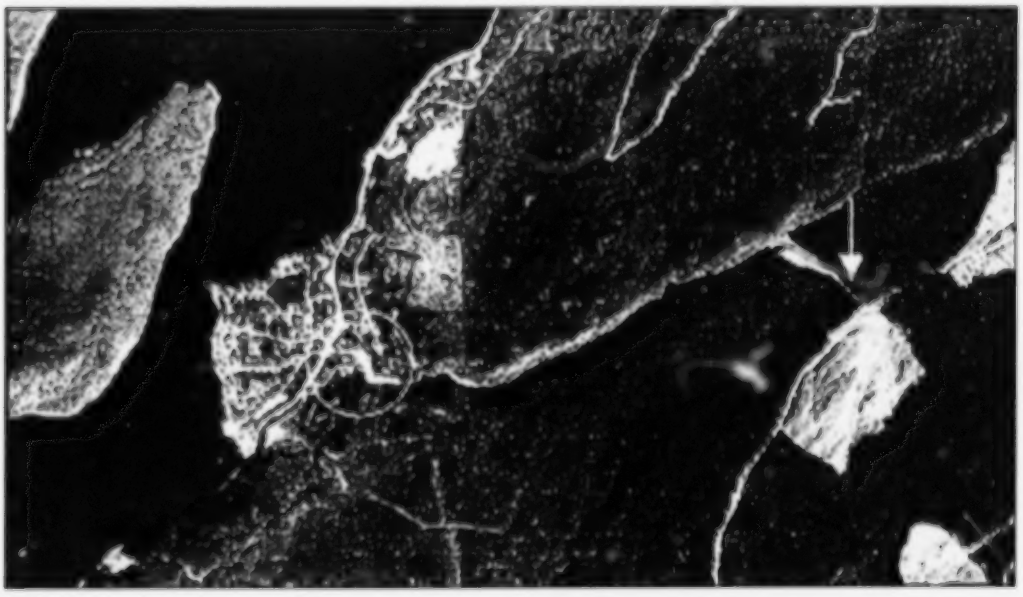
5.2.7 Hummingbird Creek Debris Flow, Mara Lake, British Columbia (82L14-15); 11 July 1997

At about 19:00 on 11 July 1997, a debris flow occurred in Hummingbird Creek (Figure 5-20), which flows into Mara Lake, approximately 7.5 km south of Sicamous, British Columbia, (Figure 5-20; Jakob et al., 2000). Debris impacted on the community of Swansea Point located on the Hummingbird Creek fan resulting in extensive damage to homes and cabins.

The debris flow initiated as a 560 m long (in slope distance) debris avalanche (Figure 5-20) on a steep (25E) northwest facing slope at approximately 1220 m.a.s.l. just below an active logging area (Figure 5-20). The initial debris avalanche involved a veneer of colluvium which overlays bedrock and dense till. Failure took place at the base of the colluvium and involved a volume of between 20,000 and 30,000 m^3 (Jakob et al., 2000). The debris flow occurred near the end of a period of above average precipitation between July 5 and 12, which also triggered other debris flows in nearby parts of the Hunters Range.

The debris avalanche swept into Hummingbird Creek at about 950 m.a.s.l., turned to the southwest, and travelled 2.5 km down the steeply confined creek channel as a debris flow. It entrained a considerable volume of material from the bed and channel margins, estimated at 50,000 m^3, before debouching onto the fan at approximately 400 m.a.s.l. The total volume of the debris flow as it reached the apex of the fan is thus estimated to have been 70,000–80,000 m^3 (Jakob et al., 2000).

Figure 5-20 Aerial photograph of the path of the Hummingbird Creek debris flow. Source debris avalanche is arrowed, and the impact zone on the Swansea Point fan is circled. Mara Lake is visible at left (British Columbia aerial photograph 15BCB97069 taken on 11 August 1997).



Most of the debris was deposited on or just above the apex of the fan, but some travelled through the community of Swansea Point on the shores of Mara Lake, destroying a highway bridge on British Columbia Highway 97A and damaging a number of homes. Massive boulders (Figure 5-21) were deposited in the debris flow path just upstream of homes on the fan. Deposits of previous debris flows are exposed in the fan.

Figure 5-21 View of lower part of 1997 debris flow path showing destruction of forest along northern margin of debris flow. Note large boulders transported by debris flow and person for scale (photograph by S.G. Evans, September 1997).

5.2.8 Five-Mile Creek Debris Flows Near Banff, Banff National Park, Alberta, 4 August 1999

At about 18:45 on Wednesday, 4 August 1999, a substantial amount of water, mud, boulders, and tree debris coming from the Five-Mile Creek buried all four lanes of the Trans-Canada Highway about 5 km west of the main exit to Banff, Alberta (Figure 5-22).

The four meter diameter culvert beneath the highway was rapidly filled by boulders and tree limbs, and then about 200 m of the highway was covered by debris varying in thickness from 0.5 m to 2 m (Figure 5-22; Couture & Evans, 2000a).

The Five-Mile Creek debris flow was triggered by a localized, high-intensity rainfall located above the valley and adjacent mountain ranges. Although two local climate stations did not

record any unusual climatic event, such as heavy precipitation, Banff Park wardens confirmed that a severe thunderstorm occurred a few hours before the debris flow. However, climate data shows that the total precipitation for July 1999 exceeded by twice the mean monthly precipitation recorded over a period of 100 years (Environment Canada). This suggests that the unconsolidated deposits on the mountain slope would have been saturated when the thunderstorm triggered the debris flow.

The debris involved in the flow originated from colluvial deposits (resulting from weathering of bare rock formations and small rockfalls) on the eastern and western slopes of the Five-Mile Creek valley (Figure 5-23). Running water from four large gullies (numbered 1 to 4 on Figure 5-23), located on the eastern slopes of Mount Cory, brought the largest portion of debris into Five-Mile Creek. More than 10 small gullies, situated on the western slopes of Mount Edith, also brought debris into the main channel (Figure 5-23).

The debris flow traveled more than 3 km from the source area, Mount Edith and Mount Cory, down to the Trans-Canada Highway (Figure 5-24). The water-debris mixture flowed down the Five-Mile Creek, eroding in-situ creek bed material and depositing debris (levees) along the creek banks. A small amount of debris, essentially mud, reached the Canadian Pacific Railway located 250 m south of the Highway (Figure 5-23), but without causing any damage.

Highway maintenance service crews worked about three weeks to resume the normal traffic, to clean off the highway, and to re-landscape creek bed portions upstream and downstream of the highway. About 45,000 m^3 of debris were cleaned out in the vicinity of the highway. Thousands of motorists were affected by the closure of the highway and either turned away to take alternative routes or were forced to wait 24 hours for the reopening of the highway. Debris also cut buried fiber optic cables, depriving the Lake Louise community of any telephone communication. The Five-Mile Creek outlet was not considered as a problematic sector in terms of damaging debris flows. No large debris flows have occurred in the last 50 years. Fortunately, the Five-Mile Creek debris flow occurred at a time of the day and the week when traffic was not heavy.

Other debris flows have recently occurred in the southern Rocky Mountains in the Banff-Bow valley area. For example, in July 1998, two debris flows, at least as large as the Five-Mile Creek event, occurred in the Spray River valley (Couture & Evans, 2000a). The debris flows temporarily blocked the Spray River, and a small lake was impounded, limiting access to a warden cabin. Once again, high-intensity rainfall was the trigger mechanism for these debris flows.

Figure 5-22 Oblique aerial photograph of the debris covering the Trans-Canada Highway about 5 km west of Banff town site, Alberta (photograph by Banff National Park, August 1999).

Figure 5-23 Aerial photograph of the Five-Mile Creek drainage basin (dashed line). Arrows indicate main gullies that brought debris into the Five-Mile Creek (Foto Flight aerial photograph FF99043 L2 #6-10, From Couture & Evans, 2000a).

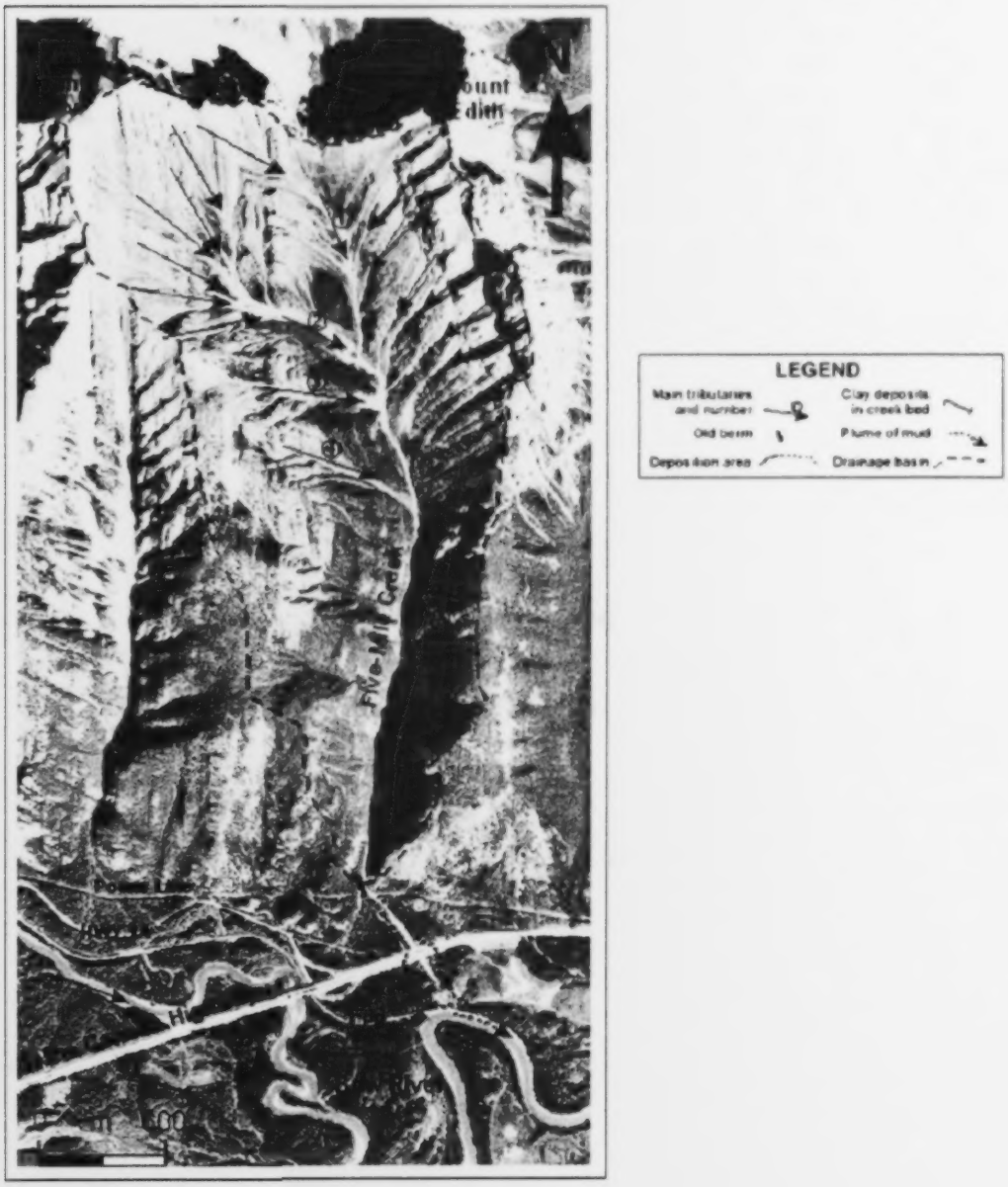


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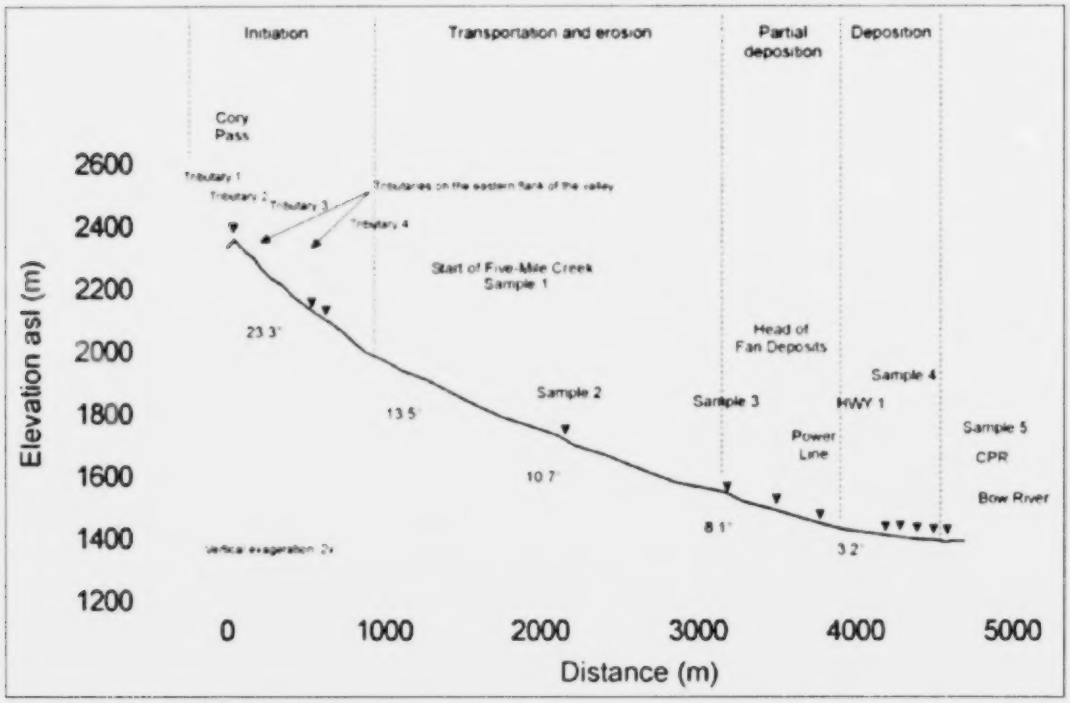
Figure 5-24 Profile of Five-Mile Creek valley from Cory Pass to Bow River. Circles indicate changes in topographic profile associated with changes in geological units (from Evans & Couture, 2000a).



5.3 Flowsides In Coal Waste Dumps

5.3.1 Coal Mine Waste Slide, Sparwood, British Columbia (82G/10); 24 November 1968

A coal mine waste slide occurred near Sparwood, in the southern Rocky Mountains of British Columbia (Figure 5-25) at about 11:45 on 24 November 1968. About 150,000 m^3 of debris (Broughton, 1992) suddenly slipped away from a dump of waste rock, consisting of sandstone, siltstone, and mudstone, on a slope overlooking the Michel Creek valley at the north end of Sparwood Ridge (Figure 5-25). The vertical height of the slide path was approximately 300 m. The debris avalanched down the slope to the floor of the valley where it covered about 375 m of British Columbia Highway 3 to a maximum depth of 10 m (Fig. 5-25). Two motorists were killed by the landslide when their car was engulfed by the debris. A contractor apparently inspected the waste dump three weeks before the failure and pronounced it safe (*Vancouver Sun,* 25 November 1968*).*

The probable cause of the slide was a failure in the toe region of the dump on a sloping foundation in weak natural soils, including glaciolacustrine clayey-silt (Broughton, 1992). Heavy rain fell in the area during the week preceding the failure and heavy snowfall was contained in

the dump during construction the previous winter. Seepage was observed in the foundation of the dump after the failure, and could have been an important factor in the failure. The stability of the dump also was compromised by the fact that it was located over a small stream in an area that had experienced prior mass movements.

In later litigation, Mr. Justice T.R. Berger found the coal company and its dump contractor negligent in "creating a vast... dump which they knew, or ought to have known, was dangerous." (*Vancouver Province,* 12 September 1972).

Figure 5-25 Oblique aerial view to the SSE of the Sparwood coal mine waste slide (Province of British Columbia (O) – 599; date of photograph 25 November 1968). Debris is seen covering BC Highway No. 3. CPR bridge over Michel Creek is visible in the foreground.

5.3.2 Gigantic Coal Mine Waste Slides In Kilmarnock Creek, British Columbia (82J/02); 26 October 1989 and 31 May 1993.

Gigantic tips of coal mine waste have been constructed at the Fording River open-pit mine, 20 km north of Elkford, British Columbia. The dumps are constructed by end-dumping into the valley of Kilmarnock Creek from huge dump trucks and consist of silstone, mudstone, and sandstone debris (Broughton, 1992; Figure 5-26). Large slope failures occur in these types of tip slopes from time to time (e.g., Hungr and Kent, 1995); pre-failure slope movements are monitored with wireline extensometers which allows failure to be anticipated (e.g., Campbell and Kent, 1995). Two major catastrophic failures have been documented on the South Dump slopes since dumping began in 1987.

On 26 October 1989 at about 06:00, a major failure occurred on the 420 m high South Spoil waste dump (Broughton, 1992; Dawson et al., 1994; Golder Associates, 1995). In 1989 the tipping platform was approximately 535 m above Kilmarnock Creek at 2200 m.a.s.l. Wireline extensometers had recorded movements of 100 to 130 cm/h on the day before catastrophic failure occurred. The failure was about 230 m wide and involved about 3.9 M m^3 of waste rock which flowed 800 m downslope into the valley, damming Kilmarnock Creek for about six days (*Vancouver Province*, October 1989).

Failure is assumed to have occurred at the interface between the dump and the surface of existing ground. The leading edge of the debris ran up the opposite slope up to a height of 40 m above the Creek. Failure was extremely rapid. Field estimates of landslide velocity suggest that the landslide had a velocity in excess of 28 m/s (Broughton, 1992); nearby foliage was damaged by the air blast (Dawson et al., 1994). A back-analysis of the failure indicated that the front of the debris reached a peak velocity of about 40 m/s (Golder Associates, 1995).

On 31 May 1993 a similar but much larger failure occurred on the South Dump (Golder Associates, 1995). On this occasion the tipping platform was at 2110 m.a.s.l. and the dump was 385 m high. The slide was 500 m wide and the flowslide involved a volume of about 8 M m^3 (Golder Associates, 1995). Debris again ran up the opposite slope and, following the slide, some debris slumped downvalley.

Figure 5-26 Aerial oblique view of waste dumps in Kilmarnock Creek in August 1995. View is to the west (photograph by S.G. Evans).

5.4 Siltflows and Silt Falls in Glaciolacustrine Silt

5.4.1 Summerland Earthfalls, Okanagan Valley, British Columbia (82E/12); 27 September 1970 and 15 September 1992

Two damaging earthfalls took place along Lakeshore Drive within the municipality of Summerland on the west side of Okanagan Lake, in 1970 and 1992. The first event occurred at about 17:00 on 27 September 1970 (*Vancouver Sun*, 28 September 1970). A block of glaciolacustrine silt fell from an almost vertical silt bluff, disintegrated, and flowed as a dry cohesionless mass of silt and silt blocks (Figure 5-27). Three houses at the base of the bluff were destroyed and one person killed. The slide covered a 60 m stretch of Lakeshore Drive with up to 4 m of silt.

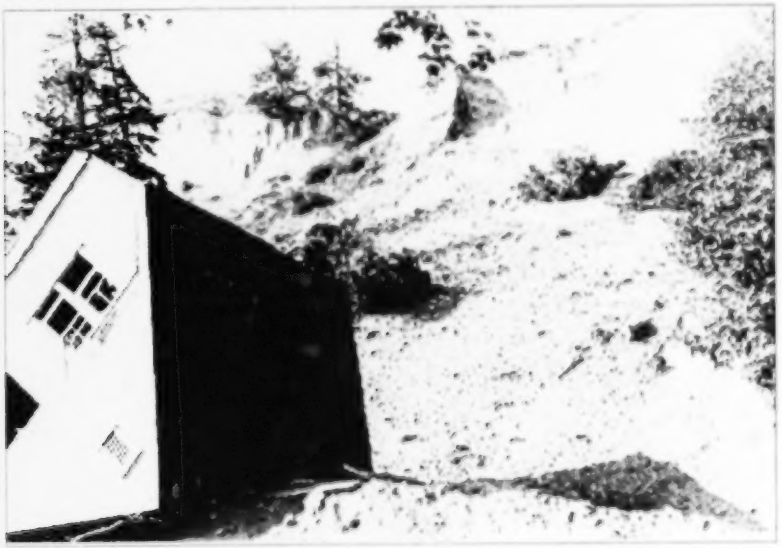
It is thought that the failure was caused by the development of water pressures in stress relief joints in the silt bluff. These water pressures probably resulted from the irrigation of an orchard on the bench above the bluff (Evans, 1982). Similar falls and subsequent flows occur on slopes outside irrigated areas only during periods of thaw and heavy rainfall.

A second earthfall occurred on Lakeshore Drive at about 17:15 on 15 September 1992 (Figure 5-29; *Penticton Herald*, 16–17 September 1992), 600 m south of the 1970 event. The landslide smashed into the garage of a lakeside home and covered a 45 m stretch of North Lakeshore Drive with up to 5 m of silt. No one was injured but a number of vehicles and boats in the garage were destroyed. Damage was estimated to be in the tens of thousands of dollars. An orchard is located at the top of the bank where the slide occurred.

The top of the bluffs in both cases is about 55 m above Lakeshore Drive.

Figure 5-27 Aerial view of 1970 Summerland siltfall site taken in 1976 (after Figure 11 in Evans, 1982). House in Figure 5-28 was located at A; source of siltfall is at B. Note orchard above source area.

Figure 5-28 Destroyed house at base of silt bluffs, Summerland, British Columbia. One person lost their life in this siltfall. Note laminated Pleistocene glaciolacustrine silts exposed in bluff face (Geological Survey of Canada photograph 157909 by S. Leaming).

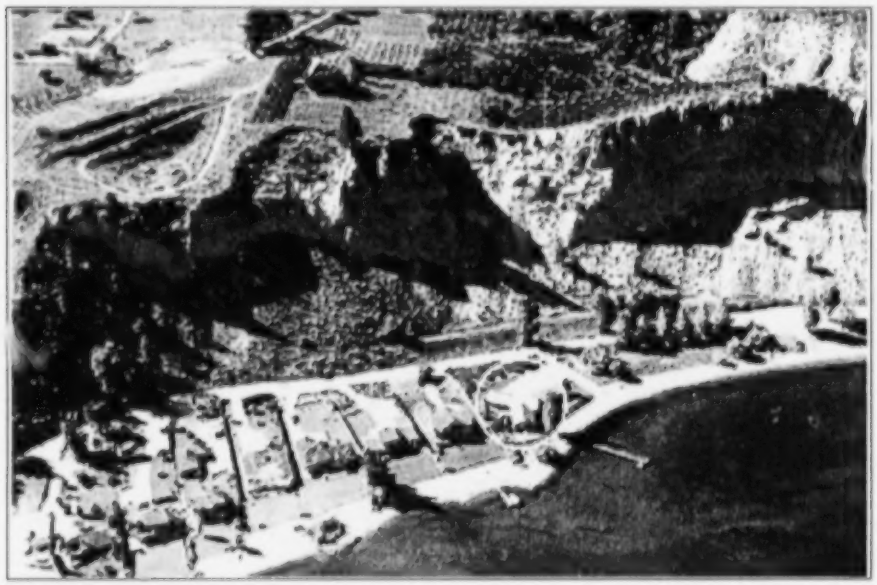


The top of the bluffs in both cases is about 55 m above Lakeshore Drive.

Figure 5-27 Aerial view of 1970 Summerland siltfall site taken in 1976 (after Figure 11 in Evans, 1982). House in Figure 5-28 was located at A; source of siltfall is at B. Note orchard above source area.

Figure 5-28 Destroyed house at base of silt bluffs, Summerland, British Columbia. One person lost their life in this siltfall. Note laminated Pleistocene glaciolacustrine silts exposed in bluff face (Geological Survey of Canada photograph 157909 by S. Leaming).

Figure 5-29 Aerial view of the site of 15 September 1992 siltfall at Summerland, British Columbia. Source area of siltfall is arrowed. A house damaged on North Lakeshore Drive is circled. Photograph taken in September 1997 by S. G. Evans. Note the construction of a protective berm at the base of the slope to prevent runout of siltfall/siltflow. Okangan Lake is in centre-right foreground.



6.0 Landslide Triggers and the Climate Change Signal

The analysis of the database indicates that many damaging landslides (particularly debris flows, debris avalanches, failures of built slopes, and landslides in glaciolacustrine materials) were triggered by precipitation. These include sustained heavy rainfall, an extreme rainfall event, and rain-on-snow events (e.g., Evans and Lister, 1984; Cass et al., 1992; Evans, 1999, Jakob et al., 2000).

The response of slopes to rainfall is locally complex and varies with such factors as vegetation, land-use, slope, aspect, and antecedent soil moisture. In the long term, however, an increase in precipitation would be expected to give rise to an increase in the frequency of damaging landslides. This effect may be offset by an increase in evaporation through an increase in temperature. In this section we examine the evidence for this first-order effect of climate change.

6.1 Climate records

Climate monitoring in the southeast Cordillera has been active intermittently since the late 19th century. The quality and the longevity of datasets varies from station to station; most stations have been active since the 1960s and 1970s, and for some, the measurements are very sporadic. This limits the depth of analysis possible, particularly when studying climate change variations when a long-term high quality dataset is essential. Slope, aspect, and elevation will influence temperature variations and precipitation distribution.

In order to study the possible effects of climate change on the southeastern Cordillera, two long-term temperature and precipitation records were assembled. The two stations represented both valley and mountainous areas; Revelstoke and Glacier National Park (GNP). Details of the stations are given in Table 6-1.

Table 6-1 Description of Environment Canada climate stations used in Section 6.0.

	Revelstoke		Glacier National Park		
Station Name	**Revelstoke Airport**	**Revelstoke**	**Glacier**	**Glacier Avalanche RS**	**Glacier NP Rogers Pass**
Station ID	1176751	1176750	1173180	1173190	1173191
Years of operation	1969–1999	1898–1969	1892–1957	1957–1965	1965–2000
Latitude	50° 57'	51° 00'	51° 14'	51° 16'	51° 18'
Longitude	118° 10'	118° 12'	117° 29'	117° 30'	117° 31'
Altitude (m)	450	456	1248	1177	1323

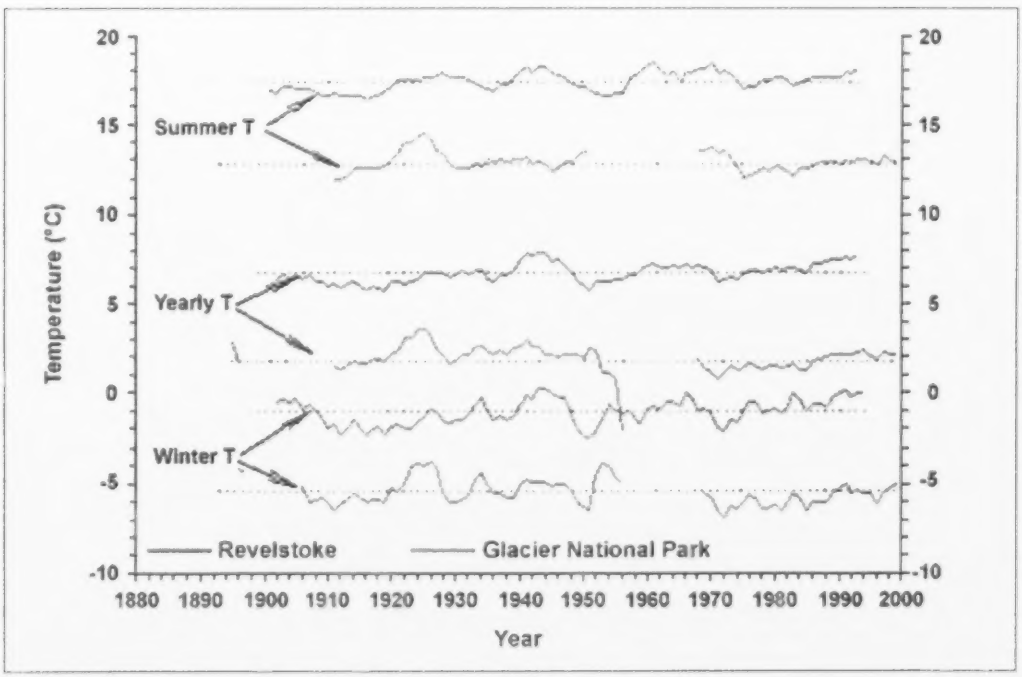
6.2 Temperature

It has been reported that during the 20th century, temperature in the southern Cordillera has increased by 0.6°C (Volume 1 of Taylor and Taylor, 1997). Warmer daily minimum temperatures during the winter and the spring have caused this statistically significant increase (Hengeveld, 1997).

Monthly temperature values for Revelstoke are a homogenized dataset taken from the Historical Canadian Climate Database of Environment Canada (http://www.cccma.bc.ec.gc.ca/hccd/). These values were mostly taken from the Revelstoke climate station (1176751) of Environment Canada. The record was complemented by values from highly correlated stations that were subject to regression analysis. This process resulted in a continuous dataset spanning from 1898 to 1995.

No long-term record that could represent Glacier National Park is available yet in the historical database. The record presented here is not as good since it was made up of two stations that did not overlap and prevented a more accurate regression analysis. Glacier station (1173180) operated from 1897 to 1957 and has a few missing months and years. Glacier National Park Rogers Pass (1176751) completes this data set with monthly values from 1965 to 2000. Values from 1957 to 1965 are missing from the record since the stations did not cover these years (Table 6-1).

Figure 6-1 Yearly, summer, and winter temperature at Revelstoke and Glacier National Park. The solid lines correspond to the five-year moving average and the dotted lines correspond to the average.



As illustrated in Figure 6-1, Revelstoke temperatures are approximately 5°C warmer than GNP, independent of the season. Temperatures are more variable at GNP; extremes are usually lower or higher than at Revelstoke. However, the trends are similar (r-value of approximately 0.7) and therefore represent a regional climate.

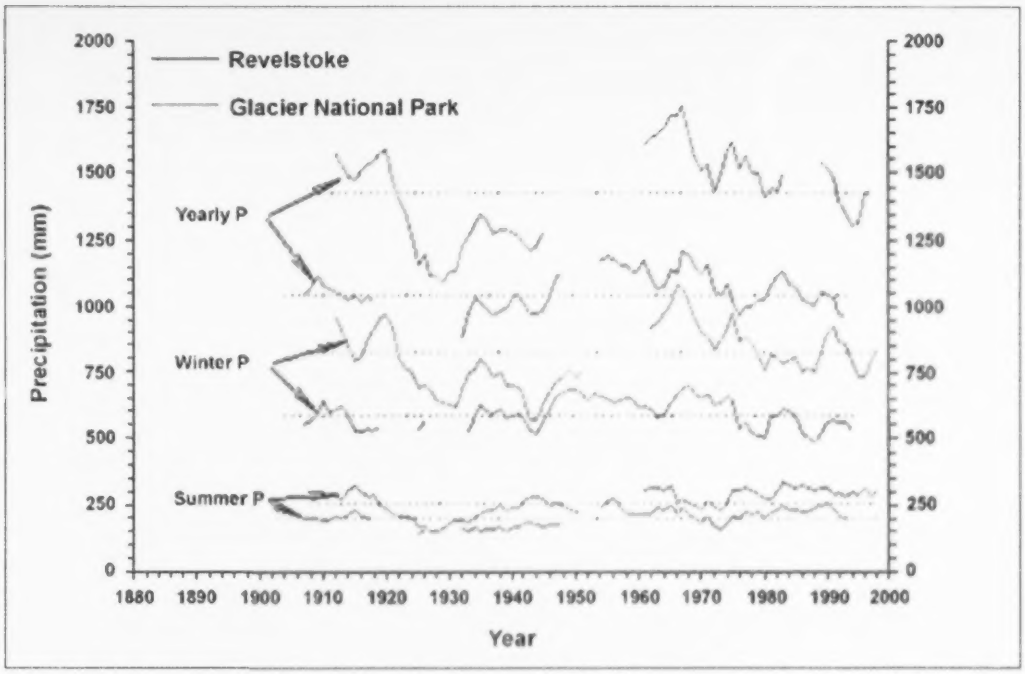
Temperature patterns are cyclic. Warmer periods are followed by cooler periods and vice versa. Temperatures decreased from the beginning of the record to reach a low around 1920. They then increased more or less continuously for 30 years. Very low temperatures were then recorded at the beginning of the 1950s. The record seems to indicate increasing temperatures during the next 15 years. However at this time, key data points are missing from the GNP record, preventing the most accurate observations and a regional analysis. Low values at the beginning of the 1970s break this pattern. There has been a warming trend since. This crucial observation is concurrent with findings published in the Canada Country Study (Taylor and Taylor, 1997).

Some observations can be made when looking at the winter and summer temperature slopes of the stations. The warming trend of the last 30 years is somewhat different between stations. Revelstoke is marginally steeper with a slope of approximately +0.07 for yearly temperature compared to +0.04 for GNP. This indicates a slightly more rapid warming for Revelstoke. Winter temperatures also have a steeper slope than summer temperatures. The summer and winter slopes for Revelstoke are +0.05 and +0.09 respectively. For GNP, the summer slope is +0.04 and the winter slope is +0.06. This indicates greater consequences of climate variations on winter conditions. They are, however, more variable from year to year than summer temperatures and consequently more difficult to evaluate.

6.3 Precipitation

The precipitation records of Revelstoke and GNP are illustrated in Figure 6-2. Both records were taken from the Environment Canada historical database and represent homogenized values. Some values are missing from both datasets. This might be explained by the discontinuous nature of precipitation and the difficulty in finding highly correlated stations. Nevertheless, values from the Revelstoke (1176751) and Glacier NP Rogers Pass (1173191) (see Table 6-1) stations are presented here. Precipitation values are in millimetres; winter precipitation is in millimetres of water equivalent.

Figure 6-2 Yearly, summer, and winter precipitation at Revelstoke and Glacier National Park. The solid lines correspond to the five-year moving average, and the dotted lines correspond to the average.



Winter precipitation is much higher than summer precipitation, with averages of 590 mm and 830 mm at Revelstoke and GNP respectively, compared to summer precipitation averages of 200 mm at Revelstoke and 260 mm at GNP.

Precipitation was very high at both locations around 1918–1919. After these wet years, there was a sharp decrease in precipitation that reached record lows around 1930. Precipitation marginally increased but remained below or slightly above average until the late 1940s. Above average precipitation followed for both winter and summer precipitation. Winter precipitation has been decreasing since the early 1970s and summer precipitation has been increasing.

It is interesting to see how both winter and summer precipitation patterns have been the same during the first 70 years on record. The trends of the latter 30 years are quite different. Winter precipitation is decreasing while summer precipitation is increasing. Increased summer precipitation can be explained by higher evaporation caused by warmer temperatures (see Figure 6-1). Since winter temperatures in this region are usually below 0°C, the evaporation rates are very low. The higher temperatures in the latter part of the 20th century would not affect winter precipitation amounts. The type of winter precipitation might however be influenced by higher temperatures. A warmer winter would theoretically generate more rain than snow if temperatures are not low enough to enable solidification. However, since winter temperatures are always low in this region, precipitation most often falls as snow. Climate variations would probably not

affect winter precipitation; the dryer trend might be explained by the cyclic nature of precipitation.
Climate change studies dealing with precipitation often look at the magnitude and frequency of extreme events. It has been hypothesized that these indicators have been increasing and will continue to increase under a doubled CO_2 concentration scenario (Kovacs, personal communication, 2001). This is particularly relevant in landslide studies given their sensitivity to precipitation.

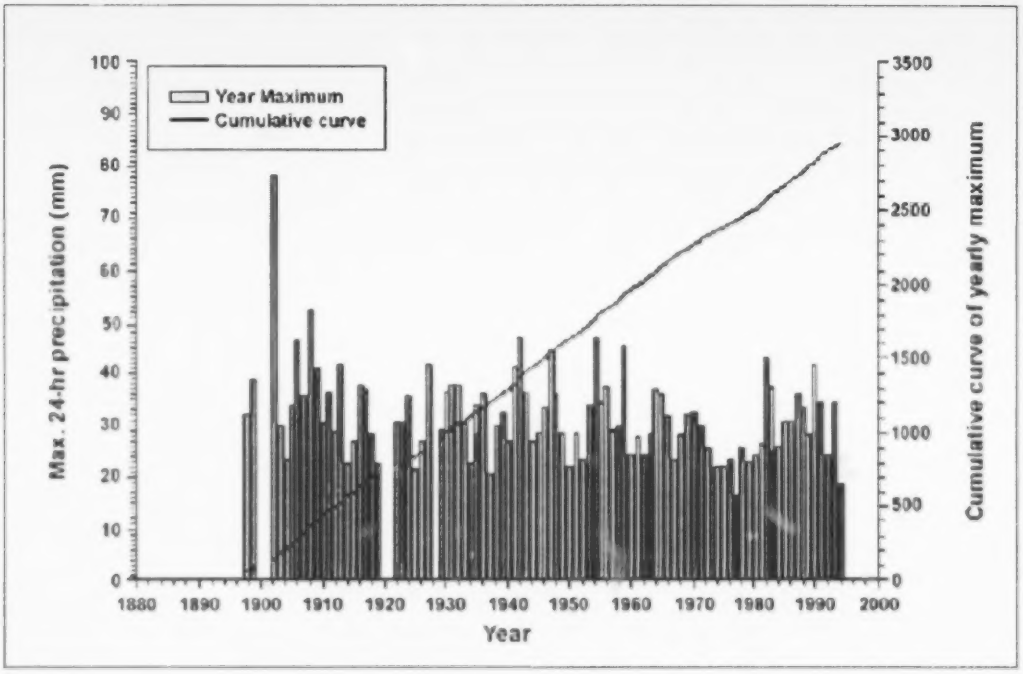
6.4 Analysis of Extreme Events – Maximum 24-hour Precipitation

The precipitation records were formed by two and three datasets for Revelstoke and Glacier National Park respectively. These stations are described in Table 6-1. The Revelstoke record corresponds to stations 1176750 and 1176751, and the GNP record to stations 1173180, 1173190, and 1173191. No years overlapped, which prevented a surely more accurate analysis based on regression modelling. A few years and some months are missing from the datasets and explain the discontinuous cumulative curve. Years with less than six months of data were removed from the record. Some caution should be used when analyzing the data.

Environment Canada provided us with the largest 24-hour precipitation values (rain or snow in millimetres of water equivalent). The heaviest daily precipitation values were reported for each month of every available year.

Magnitude – In order to determine if the magnitude of events has changed in the past century, the largest 24-hour precipitation events of every year were plotted. Figures 6-3 and 6-4 show the monthly maximum 24-hour rainfall events of the past 100 years for Revelstoke and Glacier National Park respectively.

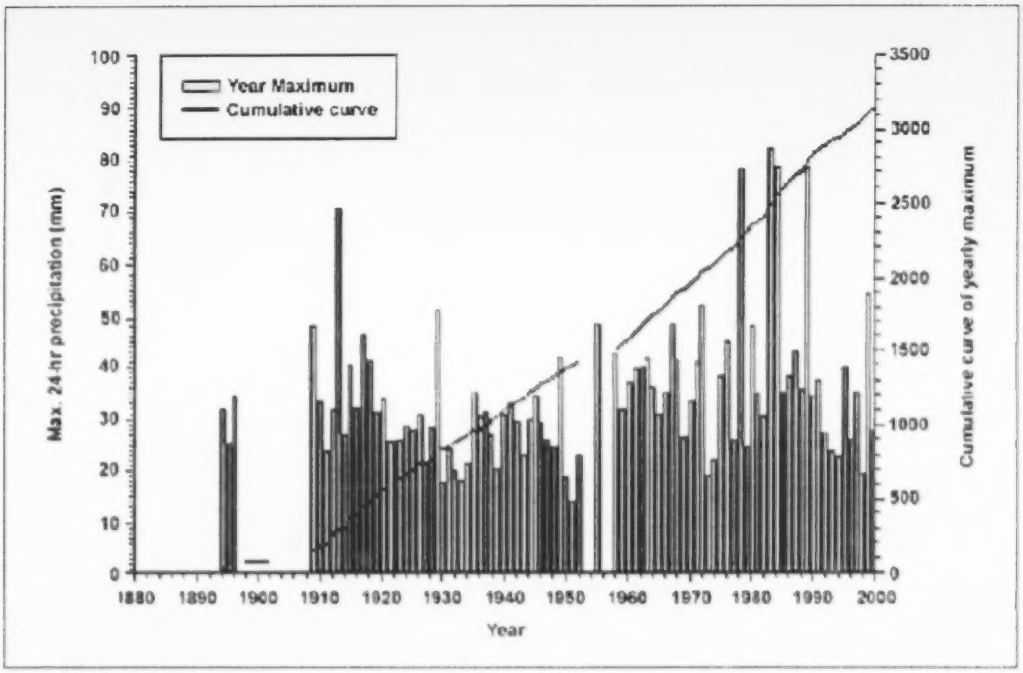
Figure 6-3 Yearly maximum values of 24-hour rainfall for Revelstoke.



There is no clear trend in the Revelstoke record (Figure 6-3). The cumulative slope is consistent throughout the record. Periods of high maximum values are followed by periods of lower values. The two largest events have occurred during the first 10 years of the record. During the first 20 years, the values are higher. The slope then becomes consistent until the early 1960s. There is a lower trend in the magnitude of the events from the 1960s to the late 1970s–early 1980s. The maximum events become of average magnitude thereafter.

The Glacier National Park record is more variable and more telling (Figure 6-4); the cumulative is not as consistent as it was for Revelstoke. Here also, the magnitudes of the events are considerably high during the first 20 years of the record. The maximum values then become lower until approximately 1950. After this time and until the early 1970s, the values are generally higher. From the mid-1970s to the early 1990s, values are extremely high: four of the largest rainfall on record occurred during the last 25 years.

Figure 6-4 Yearly maximum values of 24-hour rainfall for Glacier National Park.



The maximum events at Revelstoke have mostly occurred in the fall (September and October inclusively). Of the 13 events that have exceeded 40 mm over the span of the century, eight were in the fall. The distribution of events is different at GNP. They occurred through the year except during the spring. A total of 22 precipitation events exceeding 40 mm were counted, for which eight occurred in the fall (September and October inclusive), six in the winter (November to March inclusive), one in the spring (April to May inclusive), and seven in the summer (July and August inclusive).

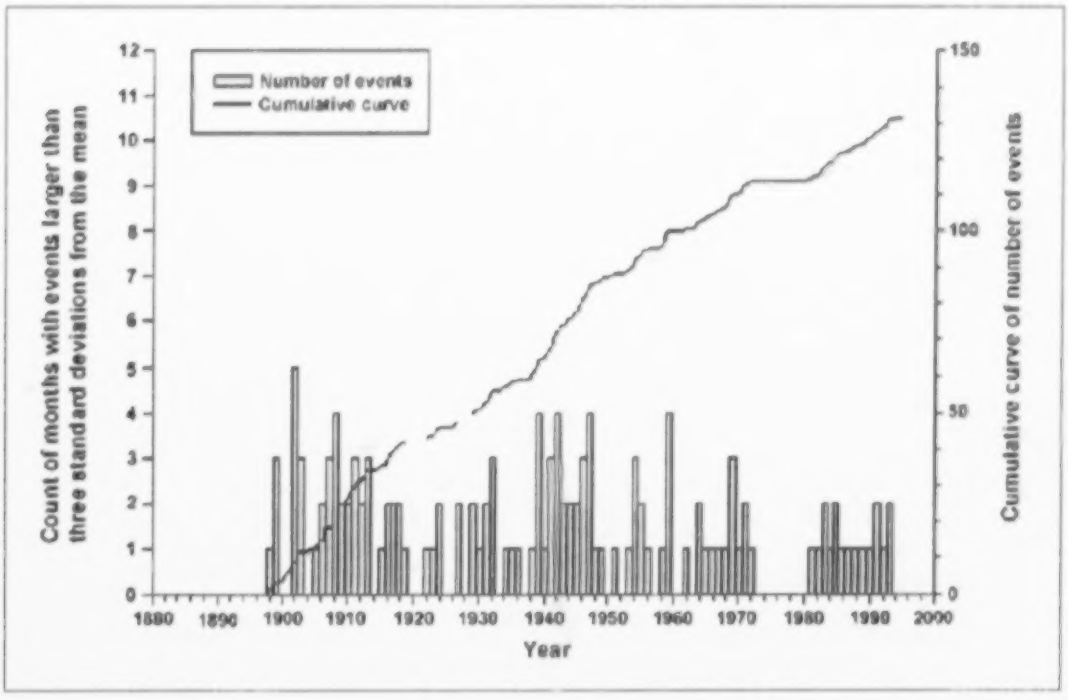
Frequency – to determine whether extreme events have recently increased in frequency, a dataset was built based on the number of events per year exceeding three standard deviations from the mean. The initial dataset is the same as the one used above (i.e. maximum 24-hour precipitation per month). To avoid biases, standard deviations were found per month (Table 6-2). Records of events larger than three standard deviations ('extreme events') from the mean of the maximum monthly 24-hour rainfall were established for the two areas and are shown in Figures 6.5 and 6.6.

From the beginning of the measurements to approximately 1913, frequency of extreme events at Revelstoke is high (Figure 6-5). Extreme 24-hour events occurred during at least one third of the months in a year. Frequency of extreme events was high from 1940 to 1949. The next decade was also high with two years having recorded three or four extreme events. The frequency of extreme events has decreased since then. Events at Revelstoke have been uncommon, with only one or two extreme events per year.

Table 6-2 Standard deviations of individual months for the Revelstoke and Glacier National Park datasets.

	Revelstoke dataset	GNP dataset
January	8.4	7.3
February	9.0	6.1
March	8.4	7.3
April	8.0	7.0
May	8.5	8.9
June	10.7	10.8
July	11.1	12.5
August	10.8	11.7
September	11.6	12.8
October	13.2	12.8
November	10.4	12.5
December	9.9	6.4

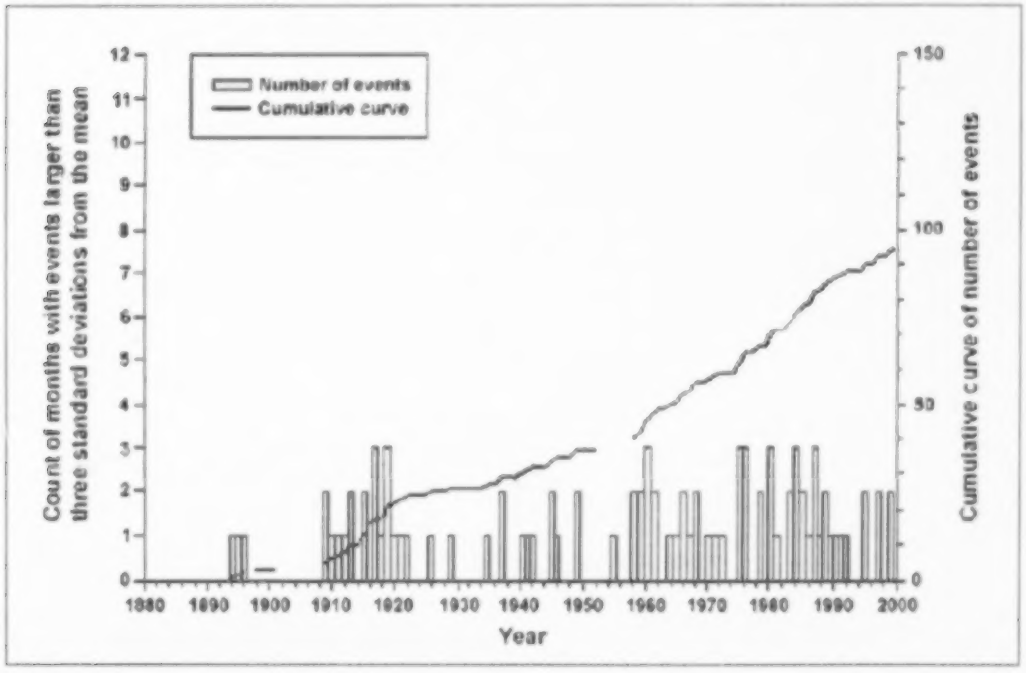
Figure 6-5 Count of months with events larger than three standard deviations from the monthly mean in Revelstoke.



Data at GNP is missing at the beginning of the 20th century so comparison with Revelstoke is not possible at this time. However, it is evident that extreme events are less common at GNP than they are at Revelstoke. The maximum number of months per year with extreme events at GNP is three. Compare this to Revelstoke, where three events per year have occurred three times.

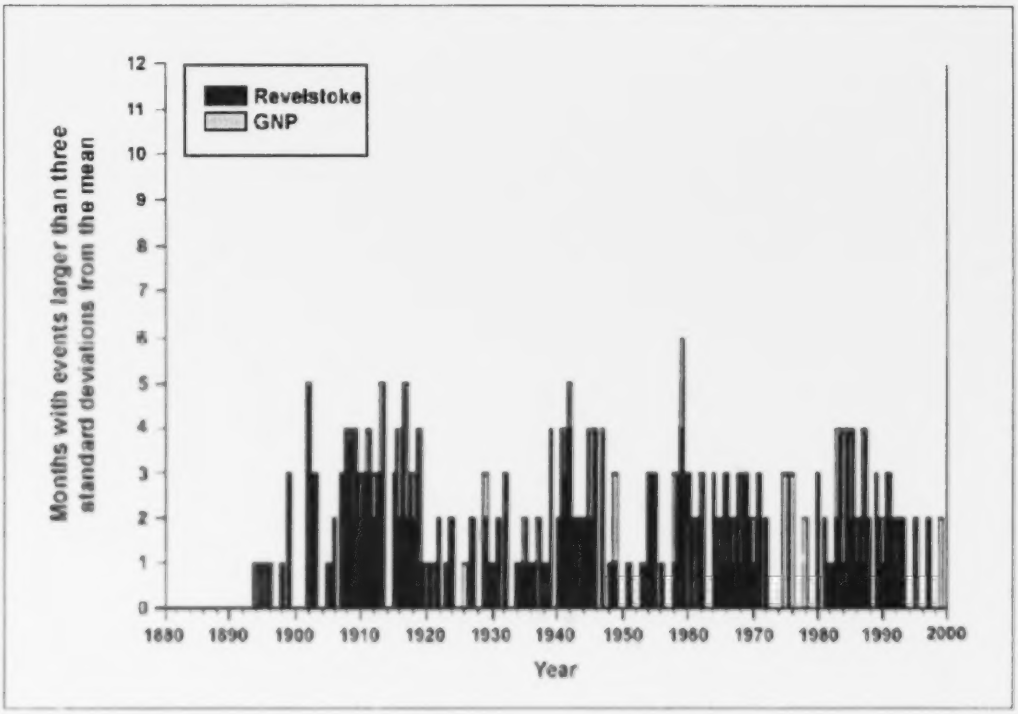
Figure 6-6 shows that the count of events is high from the beginning of the record until 1920. A long-term low then settled-in until the late 1950s when the occurrence of extreme events increased. The number of extreme 24-hour events has been high ever since. Three events per year have occurred at regular intervals, and these high-frequency event years have mainly alternated with years in which two extreme events occurred.

Figure 6-6 Count of months with events larger than three standard deviations from the monthly mean in Glacier National Park.



It is difficult to assess the changes in precipitation trends since precipitation is very local and discontinuous. Revelstoke and GNP, which are 55 km away, illustrate this challenge. Figure 6-7 shows the number of extreme events per year for both stations. It is obvious here that no generalizations pertaining to the timing of these events can be made. Both records have distinctive groupings.

Figure 6-7 Comparison of the number of months having extreme events for Revelstoke and Glacier National Park.



The last 40 years on record are significantly different for these stations. Revelstoke has low or average maximum values, while GNP has the highest maximum values on record during this same interval. Also, the number of extreme events per year has been high at GNP compared with Revelstoke, where the occurrence of extreme events has been sparser than in the past.

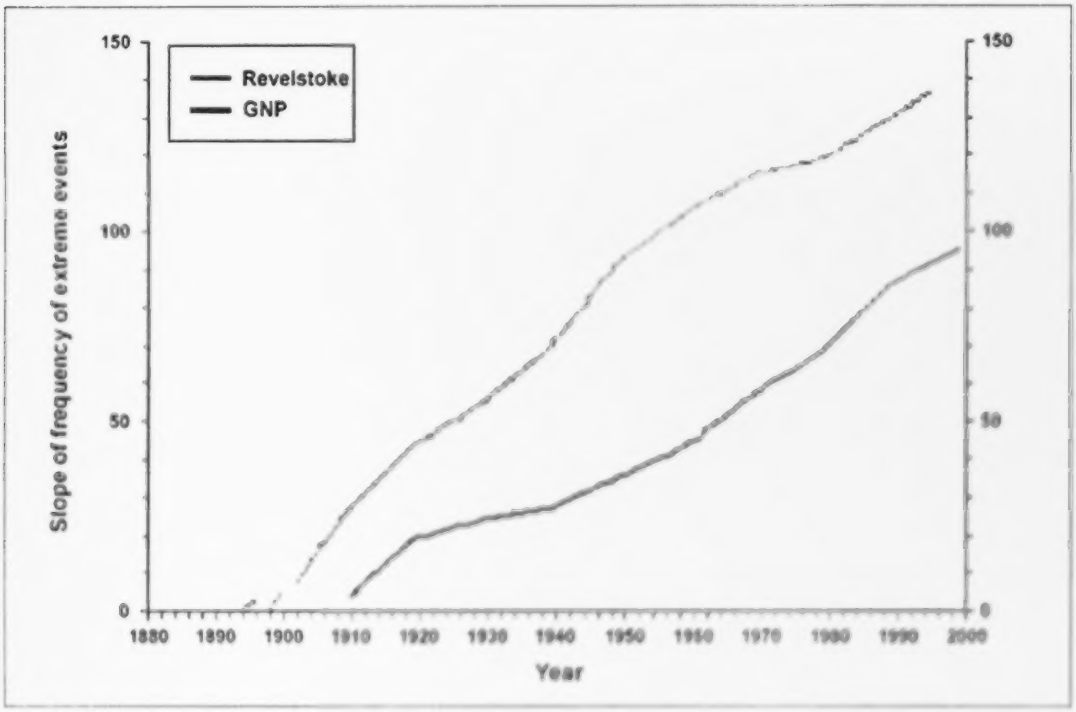
Decadal slope measurements were made and are presented in Figure 6-8. It is possible to make comparisons between slope values of the same dataset. However, since the frequency of extreme events is higher on average at Revelstoke, comparisons between records are not possible.

The slope of Revelstoke events is high until 1920 (from 1900 to 1909 the slope is +2.5; from 1910 to 1919 the slope is +1.8) where it becomes less for 20 years (from 1920 to 1929 the slope is +1.14; from 1930 to 1939 the slope is 1.4). The slope is then extremely high (+2.3) for 10 years until it drops again to +1.3 and +1.0 for the next two decades. From 1970 to 1979, the slope is at its lowest value at +0.4. Increases in the frequency of events were seen with slopes of +1.1 and +1.2 during the next 20 years.

At GNP, the slope is relatively high with an average of +1.6 from 1910 to 1919. It then becomes extremely low until 1960. Between 1920 and 1959, the slopes are equal to +0.5 and +0.3 from 1920 to 1929 and 1930 to 1939 respectively. From 1940 to 1959, the slope is equal to +0.8. The

next three decades have high slope-values with averages of +1.4, +1.1, and +1.8 respectively. The slope becomes less steep thereafter with an average of +0.9.

Figure 6-8 Decade slope averages



In order to determine what parameters have most greatly affected the magnitude and frequency of 24-hour rainfall extreme events, correlations were established between the magnitude and frequency and the yearly temperature and precipitation at Revelstoke and Glacier National Park (see Figures 6-1 and 6-2). The results (r-values) are presented in Tables 6-3 and 6-4.

Table 6-3 Correlation of magnitude and frequency of extreme precipitation events and yearly climate for Revelstoke.

	Temperature	**Precipitation**
Magnitude of precipitation	-0.023	0.911
Frequency of precipitation	0.401	0.711

Table 6-4 Correlation of magnitude and frequency of extreme precipitation events and yearly climate for Glacier National Park.

	Temperature	Precipitation
Magnitude	0.241	-0.286
Frequency	0.142	-0.023

Correlation results are significantly better for Revelstoke. While Revelstoke temperatures might affect the frequency of extreme events, the highest correlations are with yearly precipitation. Wet years are associated with frequent and with high-magnitude events.

At GNP, there is no relation between magnitude and frequency of extreme events with temperature or precipitation. Extreme events could consequently be associated with short-term precipitation activities that would probably result from micro-scale precipitation anomalies. This observation concurs with the inconsistent nature of GNP climate. The varied topography of the GNP area coupled with the large altitudinal gradient has resulted in its own microclimate.

7.0 Development of a Regional Landslide Risk Model

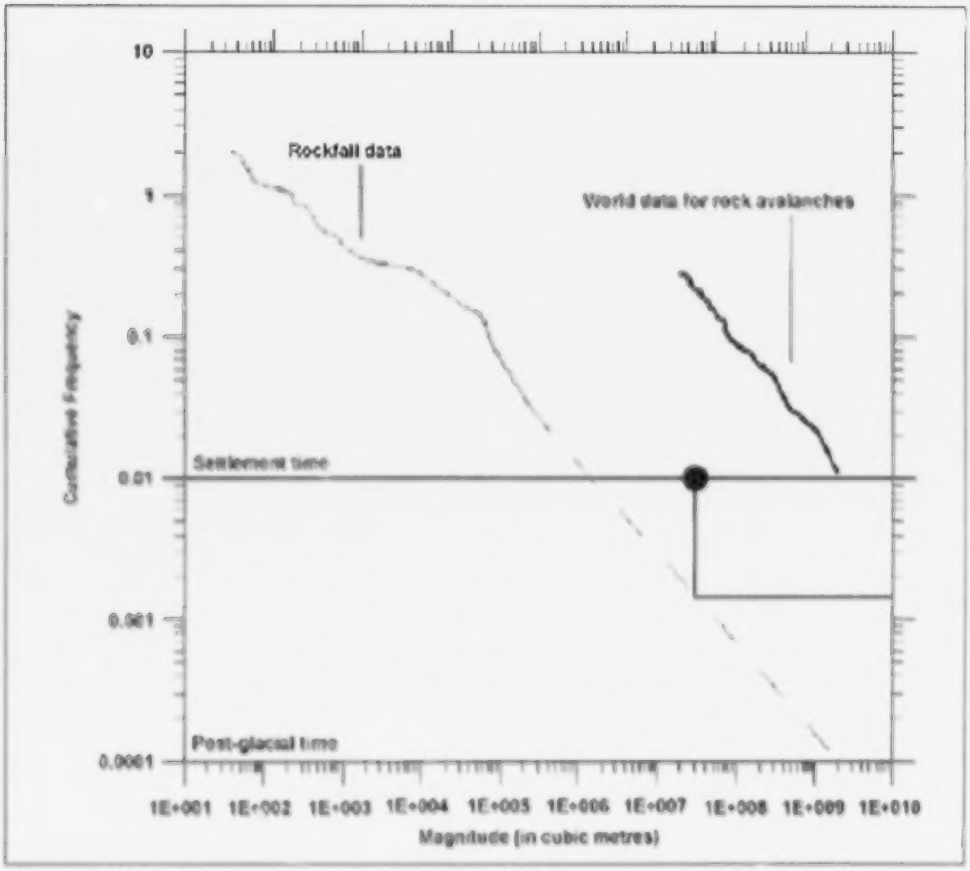
Landslide risk (Evans, 1997) is defined as the product of some measurable consequence of an event and the probability of that event (or hazard) occurring (Evans, 1997).

7.1 Hazard

The development of a regional landslide risk model is complex and has to take into account the range of damaging landslide types in the region. Analysis of the database shows that damage results from rock slope failure, debris flows and debris avalanches, failure in built slopes and instability in slopes consisting of glaciolacustrine silt. These four groups of landslides show differing magnitude-frequency relations since human and natural factors may trigger them, or at least pre-condition their failure, and thus alter their frequency.

In the case of rock slope failure, which has been responsible for the largest life loss in the region, data obtained during this study allows a first-order magnitude-frequency relation to be developed. Using methods similar to that outlined by Hungr et al. (1999), and Evans (2002) data from rockfall maintenance records and other data is plotted in (Figure 7-1) assuming that the region was deglaciated 10,000 years ago and that the length of settlement in the area is roughly 100 years.

Figure 7-1 First-order magnitude-frequency relation for rock slope failure in the southeastern Cordillera. Rockfall data is from railway maintenance records and world data for rock avalanches (1900–2000) is from unpublished data. Settlement time and Post-glacial time are approximated. The position of the 1903 Frank rock avalanche is denoted by black dot (see text for discussion).



The rockfall data is extrapolated to higher magnitudes on a magnitude-frequency (M-F) line parallel to the world data (Evans, 2002) and intersects the "one in post-glacial time" at a magnitude of about 109 m. This corresponds to the estimated volume of the largest rock avalanche in the region, the Valley of the Rocks landslide.

The Frank Slide (Figure 7-1) occurred in 1903 and thus plots on the settlement time line suggesting a frequency of 1/100. However, its true position on the M-F line suggests a frequency of nearer 1/1000 years (Figure 7-1). This estimate of frequency for a 30 M m^3 rock avalanche suggests a spatial frequency of about 1.12×10^{-4} per year per 10,000 km^2, a value comparable to the European Alps (Evans, 2002).

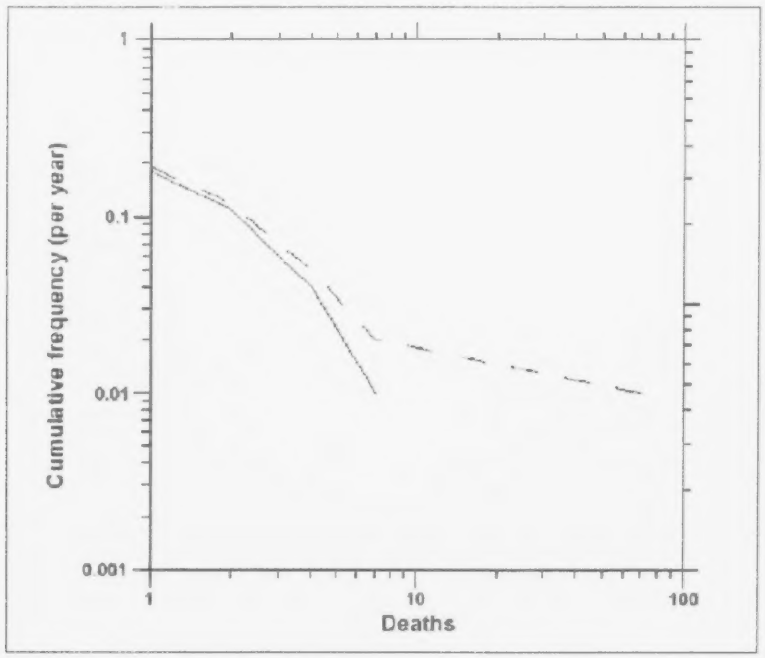
In viewing this analysis of the Frank Slide frequency it may be argued that human activity, in the form of mining at the base of the slope, had the effect of increasing the frequency of the Frank Slide by an order of magnitude.

With respect to risk calculations, it is clear that casualties of the magnitude suffered at Frank may only be sustained at sites with a relatively high population density. The region is sparsely populated and thus these sites are limited to settlements. Further, since rock avalanches are almost exclusively limited to the Foreland Belt such losses may only be expected at settlements in the Rocky Mountains.

7.2 Regional Risk Envelope

Using the method outlined by Evans (1997) a regional risk envelope was constructed on the basis of data contained in the database (Figure 7-2). It is seen that the inclusion of the death toll at Frank severely distorts the risk envelope since it produces an anomaly in the frequency of large death events. A data set excluding the Frank toll yields an envelope that is probably more suggestive of a regional risk envelope (Figure 7-2).

Figure 7-2 First-order regional landslide risk envelope for southeastern Cordillera. Dashed line includes the Frank casualties in the data set and the solid line excludes this data.



8.0 Summary

This report has focused on the record of damaging landslides in the southeastern Cordillera. The area of the region studied is 88,732 km^2 and its population is 475,220, yielding a population density of 5.4 persons/km^2. The population density is less than most countries in the world and is just a little more than the average for Canada as a whole (3.36 persons/km^2).

Despite this fact, the region experienced Canada's most deadly landslide disaster in 1903 when the Frank Slide, only the second known rock avalanche to have occurred in the region in historical time, smashed into part of the mining town of Frank. The Frank occurrence significantly distorts the regional landslide risk envelope for the southeastern Cordillera.

Magnitude and frequency relations show that the Frank rock avalanche was a 1:1000 event initiated by human activity. Landslides from massive rock slope failure in the southeastern Cordillera have a background frequency comparable to the European Alps.

Smaller magnitude damaging landslides are more common. Rainfall triggered debris flows and debris avalanches have impacted on communities and infrastructure with deadly effect. Rockfalls are common and have also impacted on communities and infrastructure but with lesser effect. Instability in slopes consisting of glaciolacustrine materials is an ongoing geotechnical problem in the region.

Rapid landslides in built slopes are an important component of the regional landslide hazard with failure having taken place in coal mine waste dumps and highway and railway embankments.

Landslide frequency data in the southeastern Cordillera are distorted by human activity such as forestry practices, mining, irrigation, and infrastructure development. This distortion was probably most marked in the early phase of economic development in the region which was largely unregulated.

Many damaging landslides have been triggered by rainfall, which makes the region's landslide hazard sensitive to climate change. Analysis of century long climate data has indicated an increase in yearly temperature over the past 30 years. Summer precipitation has also increased during this same timeframe; increases in extreme events or in their frequency are yet to be seen.

Linear infrastructure elements in the region are more vulnerable to damaging landslides than are fixed communities.

Some landslides entering lakes in the region have generated significant displacement waves.

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